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CONTROL-DISPLAY INTEGRATION PROGRAM

# ASPECTS OF PILOT DECISION MAKING


*ALEXANDER C. WILLIAMS, JR.*
*CHARLES O. HOPKINS*

*HUGHES AIRCRAFT COMPANY*


*DECEMBER 1958*




CONTRACT NO. AF 33(616) 5135



AERO MEDICAL LABORATORY
WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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## FOREWORD

This report was prepared by the Systems Development Laboratories, Hughes Aircraft Company, Culver City, California, under USAF Contract No. AF 33(616)-5135, "Study Program for Cockpit Instrument Displays for the 1970 Era" with Dr. A. C. Williams, Jr. as Project Supervisor.

The contract was initiated by the Engineering Psychology Branch, Aero Medical Laboratory, Directorate of Laboratories, Wright Air Development Center in support of Task 71556, "Design Requirements for Decision Making Displays", with Dr. Dwight E. Erlick acting as Task Scientist. This task falls under Project 6190 of the Flight Control Laboratory, Directorate of Laboratories, Wright Air Development Center. Technical guidance was provided by Captain Edward Brown and Mr. Charles A. Baker during the preliminary phases of the program.

ABSTRACT

A detailed analysis was made of the tasks performed by the pilot of a modern airborne weapon system. The results of this analysis were coded and presented in diagrammatic form to show alternative courses of action that may result in successful completion of a mission phase. Instances of pilot decision making were identified and a way of conceptualizing decision making so as to encompass these instances was proposed.

The more prominent decision theories were reviewed briefly and the applicability of each theory to the problem of pilot decision making was considered. Problem areas requiring experimental study were discussed and some approaches to the study of these problems were suggested.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Andres I. Karstens

ANDRES I. KARSTENS
Colonel, USAF (MC)
Asst. Chief, Aero Medical Laboratory
Directorate of Laboratories

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## PREFACE

The general problem area within which this study program originated is presented below as stated in the contract statement of work.

"From extrapolation of the past and present state-of-the-art developments in Air Force Weapons Systems, it can be anticipated that the weapons systems of the near future (1970 era) will be primarily controlled by automatic equipment. However, it is also anticipated that many of these weapon systems will be manned in order to provide flexibility of the mission profiles. In such aircraft the role of the man will be primarily that of a monitor and flight program selector. Thus, the requirements for cockpit instrument displays will be different from those found in present-day aircraft. In future aircraft the informational displays should be designed to maximize (1) the ability of human operators to monitor the aircraft flight parameters, and (2) the ability of human operators to make appropriate decisions relating to flight programming."

In accordance with the reference date (1970 era) mentioned in the preceding paragraph, the study program was given the title "Cockpit Instrument Displays for the 1970 Era." The authors believe that the use of this title for the present report would be misleading for two reasons. One of these is concerned with the nature of the contents of the report, and the other is concerned with the reference date of 1970.

A study of the "decision-making" role of the human operator was considered to be the necessary first step in attacking the general problem area. The study was begun by performing a detailed analysis of the tasks required of a pilot in the operation of a complex weapon system. The results of this analysis were organized in a manner that permitted identification of instances of pilot decision making. These examples of decision making were then studied in detail and a concept of decision making believed adequate to subsume them was formulated. Following this, a survey of decision theories was made to determine which, if any, might be profitably applied to pilot decision making as it had been conceptualized. The present report contains a description of the procedure and the results of this work. Consequently, although the study program was generated as a result of anticipated display design problems, the report is concerned with the study of the human function for which displays are required rather than with the displays themselves.

The implications of the results of the study of pilot decision making are considered by the authors not to be specific to manned weapon systems of the 1970 era, but rather to be generalizable to any future manned weapon systems. In this connection, it may be pointed out that recent developments in the conquering of space flight problems by the United States and Russia have had the effect of emphasizing the importance of an understanding of the decision-making role of the human operator. There are good indications that one of the goals of the space flight programs of our own country and other countries is to put man into space. In all manned systems, with the possible exception of early experimental systems whose specific purpose may be merely to study human physiological responses to space flight conditions, the human will be required to perform those functions for which his capabilities surpass those of automatic devices. Many of these functions are included under the general heading of "decision-making." Therefore, although the title of the study program refers to the 1970 era, the contents of the report concerned with the role of the man as a decision maker are not limited to any such specific time period, particularly any such period in the relatively near future.

## INTRODUCTION

Throughout the foreseeable future there will be manned military aircraft and there may be manned space vehicles. The tasks to be performed by men in these systems will be determined when the systems are designed and will depend upon the nature of the mission to be accomplished and upon the state of the designer's art. Judging from the history of the development of manned airborne weapon systems it may be anticipated that the tasks performed by men in future weapon systems will be somehow different from the tasks currently being performed by system operators.

There is no doubt that up to the present, at least, the task of the aircrew has changed with time. For one thing, it has grown in complexity. If complexity can be measured by the number of information channels into and out from the cockpit, then to establish such a growth one need only compare the cockpit of a present day fighter-interceptor, for example, with those of its counterparts of ten, twenty, thirty and forty years ago. A second measure of complexity might be the number of formal training hours deemed necessary for a crew member to reach proficiency. These hours have also increased over the years.

The aircrewman's task has changed qualitatively over the years. In the early days of military flying the pilot, for example, was mainly engrossed in the manual flight control of his aircraft. It was not necessary to spend much time with the "housekeeping" controls of the aircraft. The fire control system demanded little attention and communications were rudimentary. As these and other system functions became increasingly complex and sophisticated the pilot found that it was necessary to spend more and more time with them. Flying the airplane became just one among many tasks to be performed. At the present time the latest interceptor design requires almost no manual flying by the pilot. An automatic flight control system flies the aircraft from shortly after takeoff to just before touchdown. The pilot is not idle however. He is busily engaged in the operation of the various aircraft subsystems, choosing modes of operation, communicating, monitoring the actual flight of the aircraft and making tactical "decisions" where necessary. This pilot's task is qualitatively very different from those of his predecessors.

A number of points can be made from this very brief resume of history. The first is that the aircrewman's task has changed because equipment has been added to the system. Operator equipment has been added sometimes in a direct effort to increase system capability, sometimes as a consequence of an increase in capability achieved another way and, occasionally in an effort to simplify the operator's task.

Adding a radar set to an interceptor is an example of an attempt to achieve a direct increase in capability for the system. Adding special engine controls such as cowl flaps or afterburner is a consequence of building engines yielding higher system performance. Providing an autopilot is an example of adding equipment to simplify the pilot's task,

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and thereby changing it.

Turning now to the future there is every reason to suppose that equipment will continue to change. It can be expected to increase in quantity as new functions and capabilities are added to systems. To offset this trend there is the considerable recent interest and activity in devising means to simplify the operator's task. This is becoming manifest, for example, in the many computational aids being provided operators in new systems, in automatic control devices, and in the design of integrated displays and controls for operator use. All these trends taken together simply indicate that the operator's task in the future will almost surely be different than it is today if manned systems continue to be used as first line tactical vehicles. The question of manned versus unmanned vehicles is not the subject of this report although the question will be raised again in a different context. At present, there appear to be definite plans for manned systems, both aircraft and satellite-type vehicles, that will extend them well into the future.

It is assumed, therefore, that (1) there will be manned systems of interest in the future, and (2) the tasks performed by the men will be in some way different from those now performed in manned systems.

What will this difference be? Again turning to an extrapolation of past trends it will be recalled that in the earlier days of flying the pilot, for example, appeared to be almost completely occupied with a continuous manual control task, i.e., manipulating the aircraft flight controls in such a way as to cause the aircraft to make good some flight path he had selected, usually by visual reference to the outside world. In the latest interceptor on the other hand the pilot is relieved almost entirely of the continuous manual control task and instead spends his time looking at instrument displays and turning switches, knobs, and other controls that were not even to be found in the cockpits of former aircraft.

A second difference is that the earlier pilot chose his flight path largely by direct view of the outside world. He could see immediately where he wanted to go with respect to the ground or with respect to the target. The modern pilot obtains only a small amount of information from this source; most of his information comes from artificial displays of one sort or another within the cockpit. The reason for this is that the information required to fly a modern mission simply cannot be obtained by direct view of the outside world. Targets must be detected when they are too far away to be seen or when weather prevents their being seen. Flight paths must be chosen with more accuracy than can be judged and instead must be precisely computed. An organized defense or attack, or simply adequate traffic control, may require that information be obtained from widely scattered sources, assembled, organized, and sent in the form of commands to the various participating aircraft — a feat that could not be accomplished through the medium of the individual pilot's own sense organs acting independently. Thus, the modern pilot receives information originating beyond the range or outside the bandwidth of his own perceptual mechanism. He depends largely upon information of this type as presented by numerous instrument displays and acts in accordance with his interpretations of what is presented. The earlier pilot did not do this.

A third difference between the two tasks is found in what might be described as the sophistication of modern systems compared with older systems. The modern complex weapon system normally offers the aircrew alternative modes of operating whereas the older systems did not, or at least only to a very limited extent. Alternative modes are provided for two reasons. They are provided as back-up modes in case of equipment failure in the primary mode. They are provided in order to counteract events that might happen during a mission, perhaps by enemy action, and that would seriously degrade the probability of mission success. An example of the former is the provision for direct manual control of the aircraft in case of failure in the automatic pilot where the autopilot is the primary mode of flight. An example of the latter is the provision for alternative armament loadings as a hedge against various enemy countermeasures. A modern weapon system may offer up to thirty or thirty-five modes of operation of the second kind — not all of equal significance. Older weapon systems seldom offered more than three or four. The choice among modes is normally made an operator function. Hence today's operator has many more choices to make than yesterday's. This is reflected in the cockpits of each system — today's with many switches and controls, yesterday's with relatively few.

A reasonable extrapolation of the past trend in operator tasks to the future suggests that operators will become less and less concerned with continuous manual control tasks and more and more concerned with the interpretation of information assembled from a variety of sources and displayed "artificially" within the cockpit and with the choice of operating mode based upon the information received. This kind of activity corresponds closely with what is commonly known as the exercise of judgement or the making of decisions.

With this background the present task was undertaken. It was felt that while the words "decision making" might generally describe what operators of weapon systems of the future could be expected to spend much of their time doing, there existed no firm understanding of what the words really mean. When it is said that an operator makes a decision, what does he really do? What implications do his actions have for the design of the system, for defining his information requirements, for specifying the necessary displays and controls? What human engineering research should be undertaken now in anticipation of the new tasks?

While it was not expected that definitive answers could be found for all these questions, it was agreed that it would be worthwhile at least to attack the problem, and this is what has been done.

The plan of attack was to proceed from the known to the unknown via whatever help existing theory could provide. The known in this case was chosen to be a new electronic and control system used in interceptor aircraft. It is just at the time of writing going into production. It is a sophisticated system and one in which the operator plays a major role. It was felt that if the operator's task in this system could be analyzed in detail, considerable information could be gained about operator decision making, at least in currently advanced systems.

Next it was hoped to organize this material in such a way that extrapolation to unknown future systems could be made. In this connection the plan was to review current human decision theory, on which there is an extensive literature, to see if it could be applied to the operator's problem, thus aiding in the extrapolation.

Finally it was the plan to speculate to some extent on answers to some of the questions asked above.

# OPERATOR DECISION ANALYSIS FOR A KNOWN SYSTEM

In the past the words "decision making" have been used to refer to what the man does in situations that appear to be quite diverse. As examples, in the context of an airborne weapon system mission, it has been assumed that the man makes a decision both when he discriminates a target echo on a radar scope and when he selects, prior to takeoff, a flight program from among many possible alternative flight programs. The decision process has been conceptualized somewhat differently in the development of theoretical models for situations that are analogous to the two airborne situations given here as examples.

One way of attacking the problem of pilot decision making would be to study the applicability of various existing models to specific instances of what has been termed decision making in the airborne situation. Rather than do this, however, it was considered desirable first to search for a way of conceptualizing decision making that would encompass the man's behavior in all situations in which it is ordinarily assumed that he makes decisions.

This kind of approach to the problem required a detailed study of a manned airborne weapon system mission in terms of the tasks performed by the man. The weapon system chosen for this mission analysis was the F-106/MA-1. The first objective was simply to study the weapon system mission and collect as much information as possible about the tasks the man performs. An attempt was made to avoid, insofar as possible, the influence of any preconceived notions about the nature of the decision process. Also, during the early stages of the analysis there was no concern about a criterion or criteria for identifying instances of decision making.

In order to simplify the task of analysis, the first effort was concerned with an idealized normal mission. A list was made of the tasks the pilot has to perform assuming that the system functions properly, the enemy obligingly appears at the proper time and utilizes no countermeasures, etc. This comprehensive list covered the pilot's activities from the time he enters the cockpit for ground checks prior to takeoff until he returns to the ramp after the successful completion of the mission.

The list was then expanded by adding to it the tasks that would be required if certain events such as system malfunctions and enemy countermeasures were to occur during the mission.

The next stage of the program consisted of attempts to incorporate this information in flow diagrams representing the alternative sequences of events that might occur during a mission. A major problem encountered at this point was that of developing a system of coding the various kinds of events for diagrammatic representation. Also, it was immediately apparent that it would be practically impossible to show all of the possible alternative sequences of events that might occur. Even when only a relatively small number of the possible adverse events that could be anticipated were considered, the diagrammatic representation became extremely intricate.

A number of schemes for coding the information and simplifying the diagram were investigated. Although the different schemes varied in certain respects they all involved essentially the same procedural approach. In each case the diagrammatic representation was constructed by starting with a set of conditions at an arbitrary point (either at takeoff or at the beginning of some particular phase of the mission). Then an attempt was made to show the various possible alternative sequences of events by successive branchings of the lines representing ongoing courses of action. The results were largely unsatisfactory so this procedure was abandoned.

The next approach that was tried involved a procedure that was somewhat the reverse of the one described above. An attempt was made to construct a diagram by starting with a relatively small number of different states of the system and then working backward, so to speak, specifying the events antecedent to these states.

The states of the system that were chosen for the starting points in this procedure were those that characterize a successful attack phase of the mission. More specifically, they were those states from which armament may be fired successfully. The states are defined by the various permissible combinations of such factors as attack geometries, radar modes, and types of armament selected.

Although the manner of devising this diagram involved working backward, the resulting symbolic structure was one that represented the successive occurrence of events in a conventional fashion. The diagram presented a clear indication of how the system, starting in a specified state at some arbitrary point, can eventually get into a mode of operation resulting in one of the system states that define a successful attack.

In order to keep the diagram as simple as possible, the sequences of events were traced back through their respective points of origin to a single common origin arbitrarily located just prior to the time of reaching the offset point*. Thus, the diagram in general represented the alternate ways in which the attack phase of a mission may be accomplished.

Three categories of events were included in the diagram. These were (1) information received by the pilot (usually visually), (2) actions taken by the pilot, and (3) actions carried out automatically by the system. For the sake of convenience these events may be referred to as (1) pilot sees, (2) pilot does, and (3) system does, respectively.

With this kind of representation of the sequences of events that

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*The offset point is a navigation point from which the target may be expected to be seen by the search radar and signifies the start of the attack phase of the mission.

may occur during the attack phase of the mission available, the next step was one of identifying the points where it can be said that the pilot makes decisions. Without making any committment as to the nature of the decision process itself, it was agreed that the pilot makes a decision each time an ongoing course of action branches into alternate courses of action as a result of the pilot's behavior. At each of these points on the diagram the following information was available: (1) the nature of the ongoing course of action, (2) the information that is presented to the pilot when an event occurs that renders this course of action no longer appropriate for successful completion of the mission, (3) the alternative course(s) of action that are appropriate, (4) the things the pilot does to change the mode of system operation to carry out an alternative course of action, and (5) the expected results of each alternative course of action.

Study of the points where an ongoing course of action branches into alternate courses of action led to a concept of decision making somewhat different from the one ordinarily advanced. It was noted that whenever an event occurs that renders an ongoing course of action inappropriate, the pilot is presented with an indication of this. If one kind of indication is presented, the pilot does something specific in response to that indication. If some other indication is presented, he does something else. In other words, for each different indication there is a prescribed appropriate course of action. The conclusion was reached that it would be profitable to conceive of decision making in terms of discriminating stimuli rather than in terms of selecting responses. For the type of semi-automatic system under consideration it seemed that when the pilot makes a decision he is not deciding "What response should I make?", but rather he is deciding "What is the state of the system?" Once he has diagnosed the state of the system the appropriate response is known. The state of the system specifies the response to be made.

How this way of conceptualizing the decision process was developed can be further clarified by describing in some detail actual sequences of events in a diagram representing the attack phase of the mission. In Figure 1 the various events are coded in terms of (1) what the pilot sees (circles), (2) what the pilot does (rectangles with rounded corners), and (3) what the system does automatically (rectangles). A shaded rectangle indicates a course of action carried out automatically resulting in successful armament firing. A cross-hatched rectangle indicates that an attack is broken off.

Since some of the events represented by the circles and rectangles are concerned with modes of system operation that are classified, the events represented by the symbols are identified only in general terms. For purposes of illustrating the nature of pilot decision making in this kind of system, however, detailed knowledge of the nature of specific events is unnecessary. The interest is not in the details of the events themselves, but rather in the relationships among the three general classes of events. The diagram is to be interpreted as follows:

The attack is considered to have its starting point at an arbitrary moment in time just after turning through the offset point. At this time the pilot sees (No. 1 on the diagram) on the radar scope the

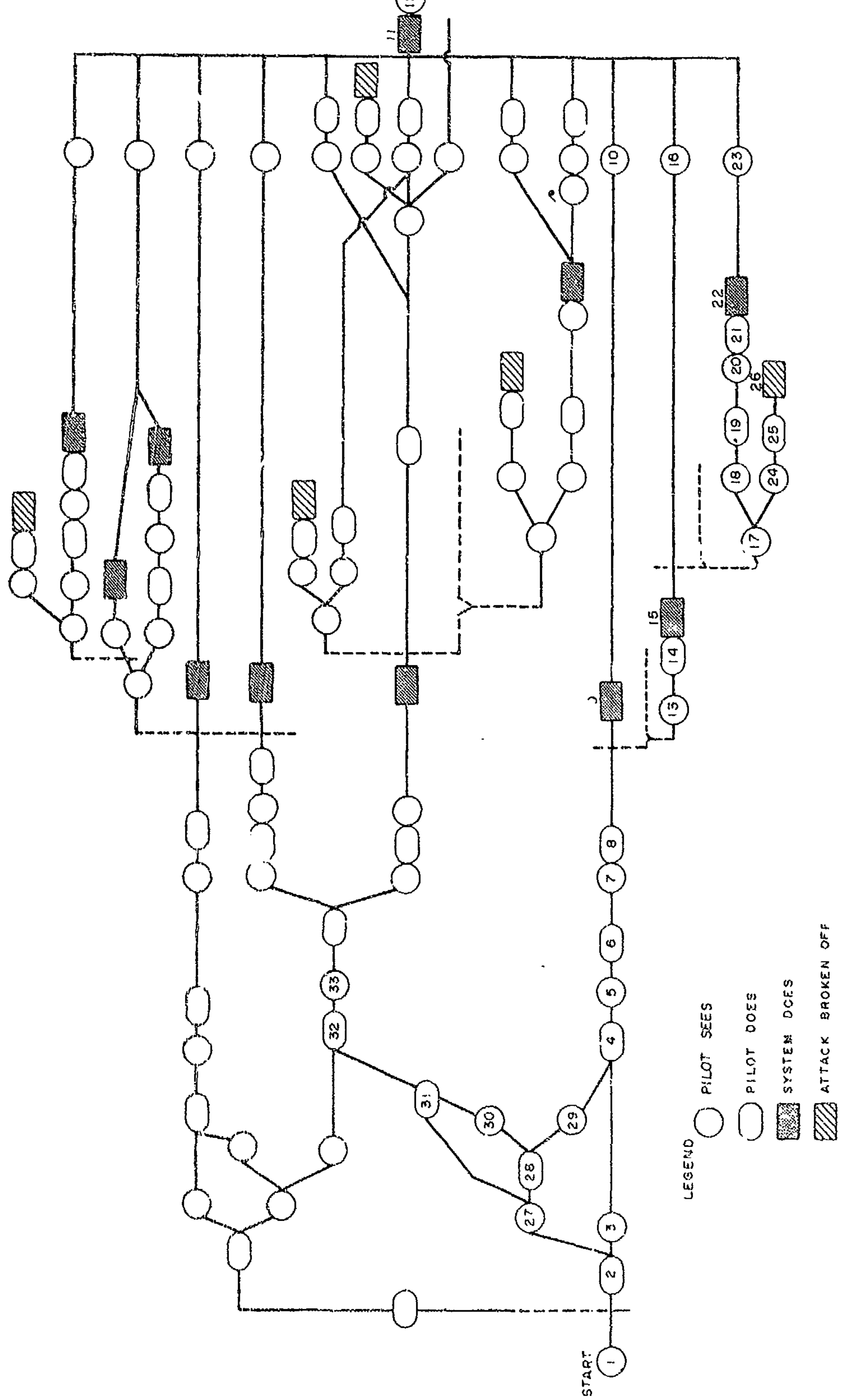



FIGURE 1. ALTERNATE EVENT SEQUENCES CULMINATING IN ARMAMENT FIRING

range sweep, antenna elevation marker, target elevation marker, target marker circle, steering dot and reference circle. Assuming that the pilot has not previously received information leading him to expect other than normal attack conditions he adjusts the azimuth scan, artificial horizon, and antenna elevation on the radar scope (2). He may then see a target echo on the radar scope (3). He depresses the action trigger (4), and the range gate marker appears on the scope (5). He adjusts the radar antenna hand control (6). The target echo and range gate marker merge, followed by the appearance of the attack display on the radar scope (7). The pilot releases the action trigger (8) and the system automatically executes the attack (9). Although the attack is executed automatically by the system, information about the progress of the attack is continuously displayed to the pilot (10). At the proper time the system fires the armament automatically (11) and a signal indicating the occurrence of this event appears on the radar scope (12).

It should be noted that under the conditions of a normal, ideal attack assumed above, the sequence of events occurring prior to initiation of the automatic flight program consists of an alternation of "pilot sees" and "pilot does" types of events. In other words, a normal sequence requires no "decisions" in the sense of selecting a course of action from among several alternatives. As a result of his training the pilot makes responses appropriate to events as he is informed of the occurrence of these events by his displays. His "decisions" are in the nature of diagnoses of the state of the system, rather than selections of courses of action.

Let us now consider the pilot's performance during a mission that departs from the "ideal" normal mission as a result of the occurrence of some unpropitious event. Consider that this event is the use of countermeasure A by the enemy sometime following the initiation of the automatic flight program. The pilot sees evidence of this countermeasure on his radar scope (13). He performs counter-countermeasure a (14) and the system automatically executes the attack (15). If no additional adverse events occur, the sequence is continued through automatic firing (11) and the displayed indication of firing (12).

As was the case in the normal attack sequence, the pilot's actions are specified by the information displayed to him. Once he has determined the state of the system (in this case, the presence of enemy countermeasure A) the response he should make is also determined. The latter is fixed by the design of the system and by the training in the use of the system that the pilot has received.

We may also consider the possibility that there is a cessation of enemy countermeasure A after counter-countermeasure a has been accomplished and the automatic flight program initiated. The pilot sees evidence of the cessation of countermeasure A on the radar scope (17). This may be followed either by the appearance of a target echo (18) or no target echo may appear (24). If the pilot correctly decides that there is a target echo (18) he adjusts the radar antenna hand control (19) and the attack display appears on the radar scope (20). He releases the action trigger (21) and the system automatically executes the attack (22) which again terminates in automatic firing (11). If the pilot correctly decides that no target echo is present on the radar scope (24) he presses the return-to-search switch (25) and the attack is broken off (26).

The various alternative sequences outlined above are sufficient to illustrate the concept of decision making arrived at through study of the F-106/MA-1 weapon system mission. Almost invariably, at the points in the mission where an ongoing course of action branches into alternative courses of action as the result of the occurrence of some unfavorable event, the alternative courses are differentiated initially by informational displays that are different, one from the other. This leads to the conclusion that it should be profitable to conceive of the decisions made by the pilot not in terms of the pilot's selection of a course of action from among the alternatives available, but rather in terms of his diagnosis of the state of the system. In other words, the pilot does not choose a course of action but he does decide what is the nature of the situation. Once he has decided what the state of the system is, the course of action is specified.

In the F-106/MA-1 system mission an exception to the rule that alternative courses of action are differentiated initially by different informational displays representing different states of the system is indicated in the diagram following the performance of event (2) by the pilot. If the enemy uses countermeasure A at this point, evidence of this event appears on the pilot's radar scope (27). The pilot is then confronted with the selection of either counter-countermeasure a (31) or counter-countermeasure b (28). The information presented on the radar scope (27) does not specify which of the two responses should be made. If the pilot performs counter-countermeasure b (28) the target echo may appear on the scope (29) or it may not appear (30). If the pilot correctly decides that there is a target echo on the scope (29) he then presses the action trigger (4) and is back on the normal sequence of events. On the other hand, if he correctly decides that there is no target echo on the scope (30) he then performs counter-countermeasure a (31), which is a response he could have made initially when he detected the occurrence of countermeasure A (27).

Thus, the alternatives (28) and (31) seem to characterize a situation of the type usually described when decision making is conceived of as the selection of a course of action from among two or more alternatives.

Actually, countermeasure A, whose occurrence is displayed (27) may be either one of two countermeasures, which while similar in nature, are most effectively coped with by means of two different counter-countermeasures. The display may not in all cases immediately indicate which of the two related countermeasures is being used. The pilot has the option of performing counter-countermeasure a (31) which will initiate a course of action that will counteract either of the two countermeasures, or of performing counter-countermeasure b (28) which will effectively inform him which of the two countermeasures is being used. Also, if he performs counter-countermeasure b and subsequently sees a target echo (29) he knows that he made the appropriate response and may continue with the normal sequence (4, 5, 6, etc.). If, however, after performing counter-

countermeasure b (28) he cannot see a target echo (30) he knows that the appropriate response is to perform counter-countermeasure a (31), which could have been made initially. The advantage of performing counter-countermeasure b initially is that, if it is appropriate, the system is immediately back on the normal sequence of events. The disadvantage of performing counter-countermeasure b initially is that if it is inappropriate, there is a penalty in the form of loss of time during the performance of counter-countermeasure b before counter-countermeasure a is eventually made. The advantage of performing counter-countermeasure a initially is that if a is appropriate the system is immediately on a sequence of events (31, 32, 33, etc.) which leads to the initiation of an automatic attack program. The disadvantage of performing a initially is that while a is effective against both countermeasures, b is more effective with one of them, and if that countermeasure against which b is more effective actually occurred, the penalty for making a is in terms of a relative decrease in system performance.

Fortunately for the pilot, the situation described in some detail above does not really constitute a decision problem. The probabilities of occurrence of the possible outcomes and the values of the possible outcomes for each of the alternatives have been considered by those concerned with the design of the system and by those concerned with planning its tactical utilization. The decision that counter-countermeasure b (28) should always be made first when there is evidence of A-type countermeasure has been made by the designers and tacticians. Thus, even though the pilot knows that alternative (31) is open to him when (27) is displayed, it is standard operating procedure for him to perform (28) first.

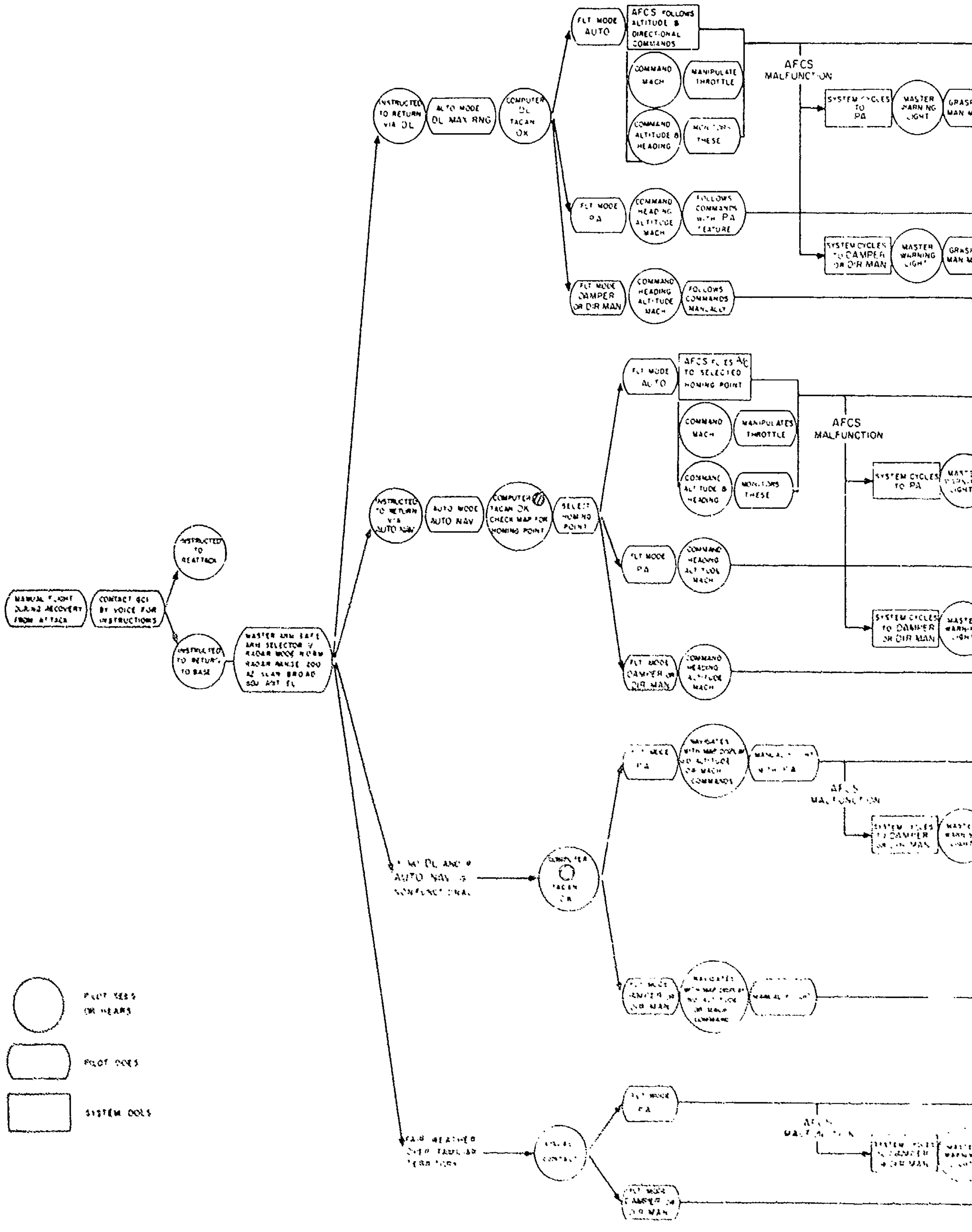
The same procedure used in the construction of the diagram representing the attack phase was used to construct a diagram of the alternative courses of action that might be carried out during the return-to-base and landing phases of the mission. This served two purposes. First, it provided a check on the applicability of the procedure and coding scheme to other kinds of situations. Second, the resulting diagram permitted a check on the generality of the concept of decision making arrived at through study of the attack phase diagram.

The diagram in Figure 2 presents the alternate event sequences for the return-to-base and landing phases. The starting points for the construction of this diagram were those states of the system from which the TRACAL approach control area may be entered. For the purpose of constructing this diagram, [illegible]3 of these states were defined by the various permissible combinations of navigational modes and flight control modes.

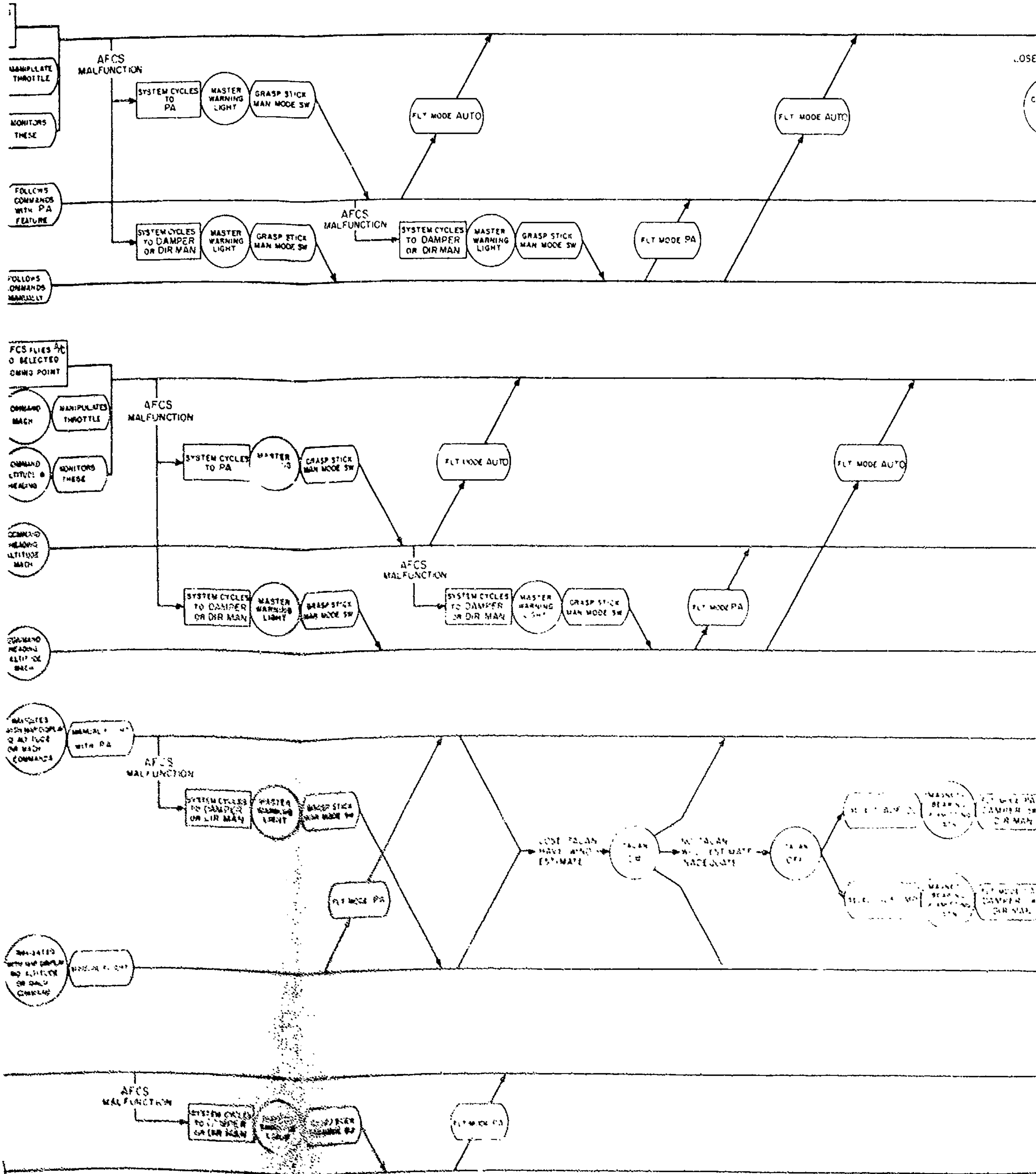
The four major navigational modes considered were DL MAX-RNG (data link maximum range), AUTO-NAV (automatic navigation), Map Display, and Visual Contact. Within the Map Display major mode there are TACAN and ADF sub-modes. Within the ADF sub-mode there are three sub-sub-modes designated ADF-DL, ADF-CMD, and ADF-DL and CMD.

The three flight control modes considered were AUTO (full automatic), PA (pilot assist), and DAMPER or DIR MAN (direct manual). It should be noted that the two DAMPER modes (PITCH AND YAW) and the DIR MAN mode are not treated separately in the diagram. The arbitrary combination of these three flight control modes permits considerable simplification of the diagram and does not appreciably affect the structure of the diagram insofar as pilot decisions are concerned.

The combinations of navigational modes and flight control modes defining the 13 states of the system are shown in Table I.



MANUAL FLIGHT DURING RECOVERY FROM ATTACK
CONTACT GCI BY VOICE FOR INSTRUCTIONS
INSTRUCTED TO REATTACK
INSTRUCTED TO RETURN TO BASE
INSTRUCTED TO RETURN VIA DL
AUTO MODE DL MAX RNG
FLT MODE AUTO
AFCS FOLLOWS ALTITUDE & DIRECTIONAL COMMANDS
COMMAND MACH
MANIPULATE THROTTLE
COMMAND ALTITUDE & HEADING
AFCS MALFUNCTION
SYSTEM CYCLES TO PA
MASTER WARNING LIGHT
FLT MODE PA
COMMAND HEADING ALTITUDE MACH
FOLLOWS COMMANDS WITH PA FEATURE
SYSTEM CYCLES TO DAMPER OR DIR MAN
MASTER WARNING LIGHT
FLT MODE DAMPER OR DIR MAN
COMMAND HEADING ALTITUDE MACH
FOLLOWS COMMANDS MANUALLY
INSTRUCTED TO RETURN VIA AUTO NAV
AUTO MODE AUTO NAV
COMPUTER TACAN OK CHECK MAP FOR HOMING POINT
FLT MODE AUTO
TO SELECTED HOMING POINT
COMMAND MACH
MANIPULATES THROTTLE
MONITORS THESE
AFCS MALFUNCTION
SYSTEM CYCLES TO PA
FLT MODE PA
COMMAND HEADING ALTITUDE MACH
SYSTEM CYCLES TO DAMPER OR DIR MAN
FLT MODE DAMPER OR DIR MAN
COMMAND HEADING ALTITUDE MACH
PILOT DOES
SYSTEM DOES



AFCS MALFUNCTION
MANIPULATE THROTTLE
MONITORS THESE
SYSTEM CYCLES TO PA
MASTER WARNING LIGHT
GRASP STICK MAN MODE SW
FLT MODE AUTO
FOLLOWS COMMANDS WITH PA FEATURE
SYSTEM CYCLES TO DAMPER OR DIR MAN
FLT MODE PA
FOLLOWS COMMANDS MANUALLY
MANIPULATES THROTTLE
COMMAND MACH
SYSTEM CYCLES TO PA
MANUAL FLIGHT WITH PA


2

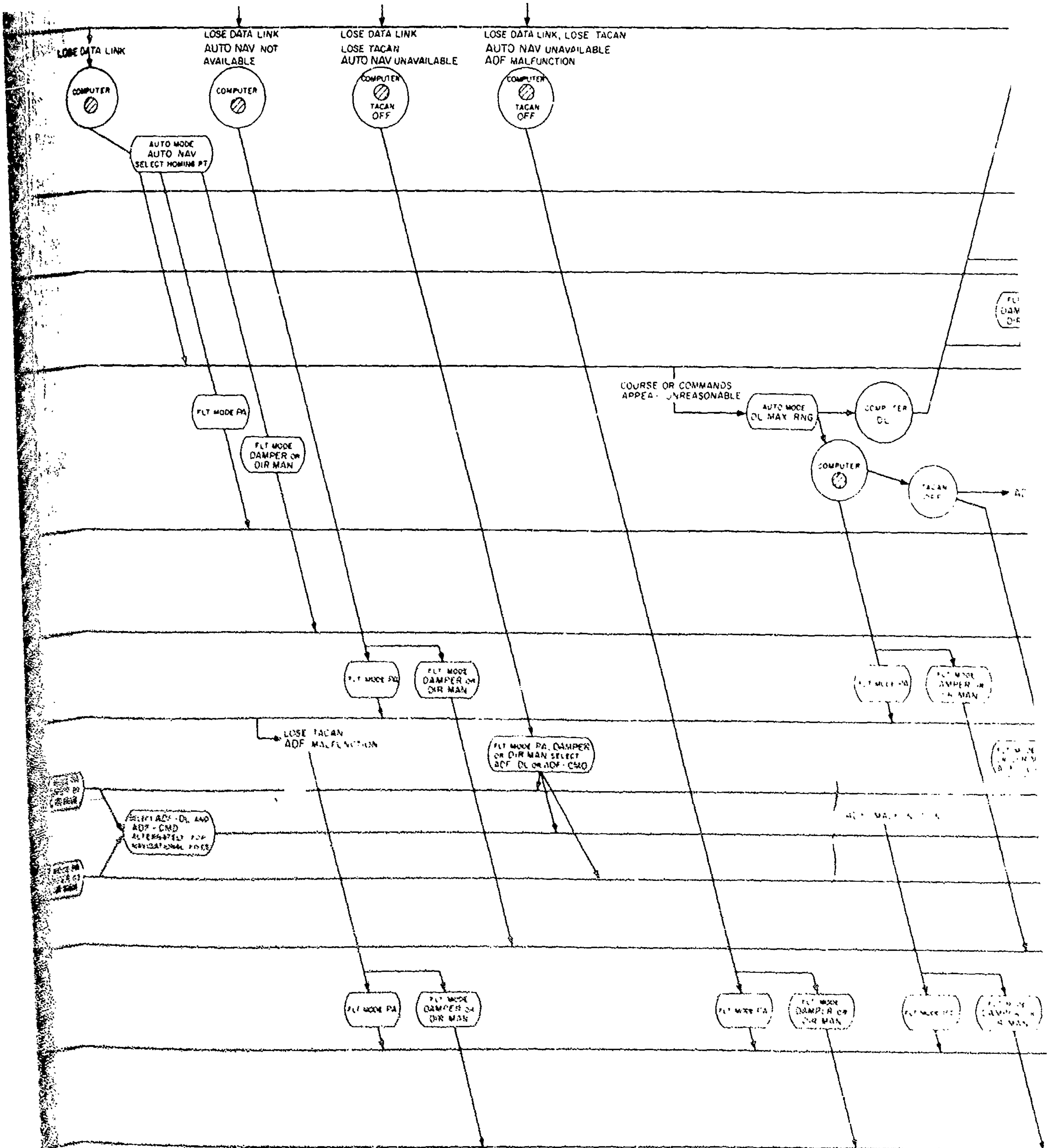
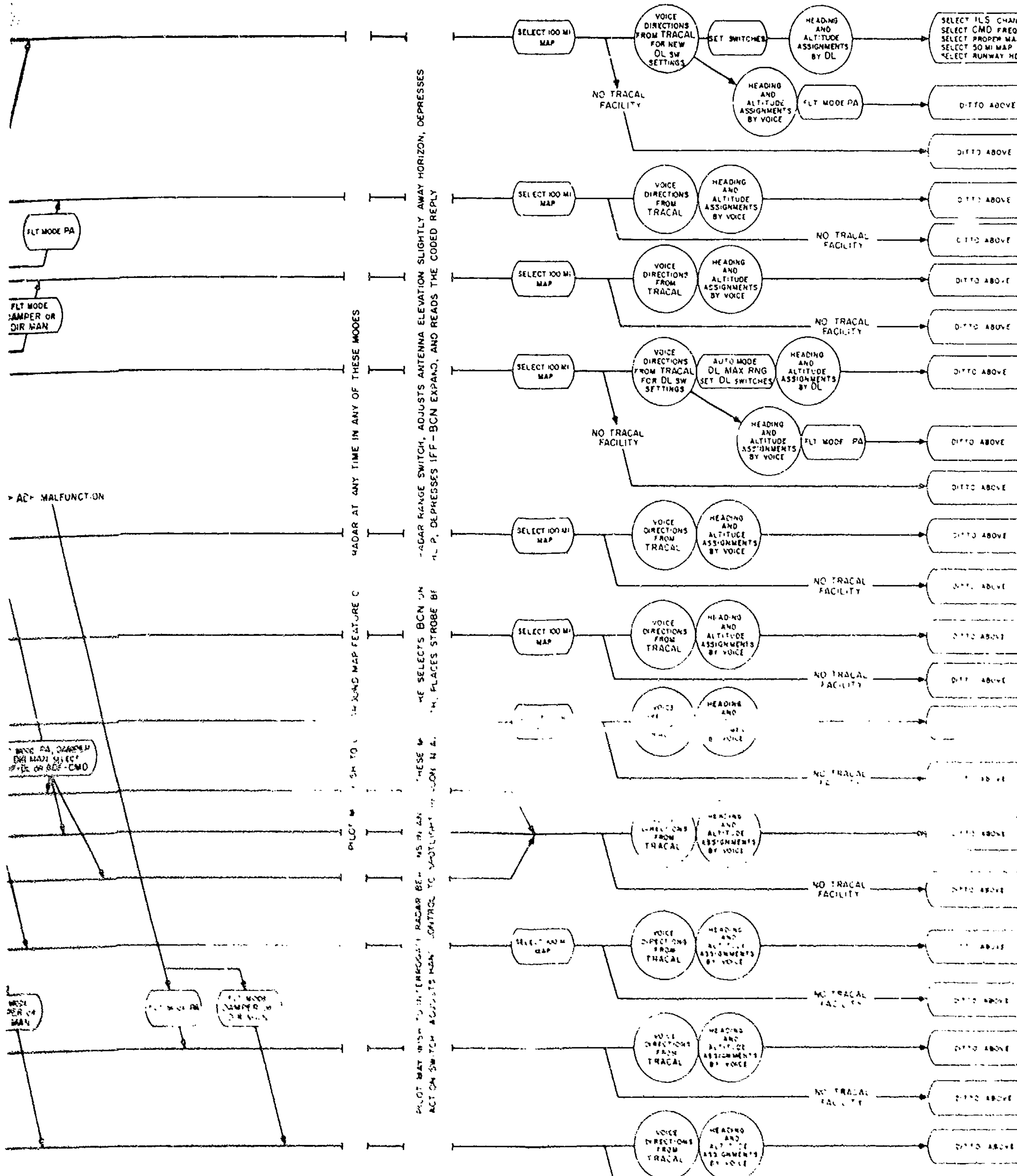
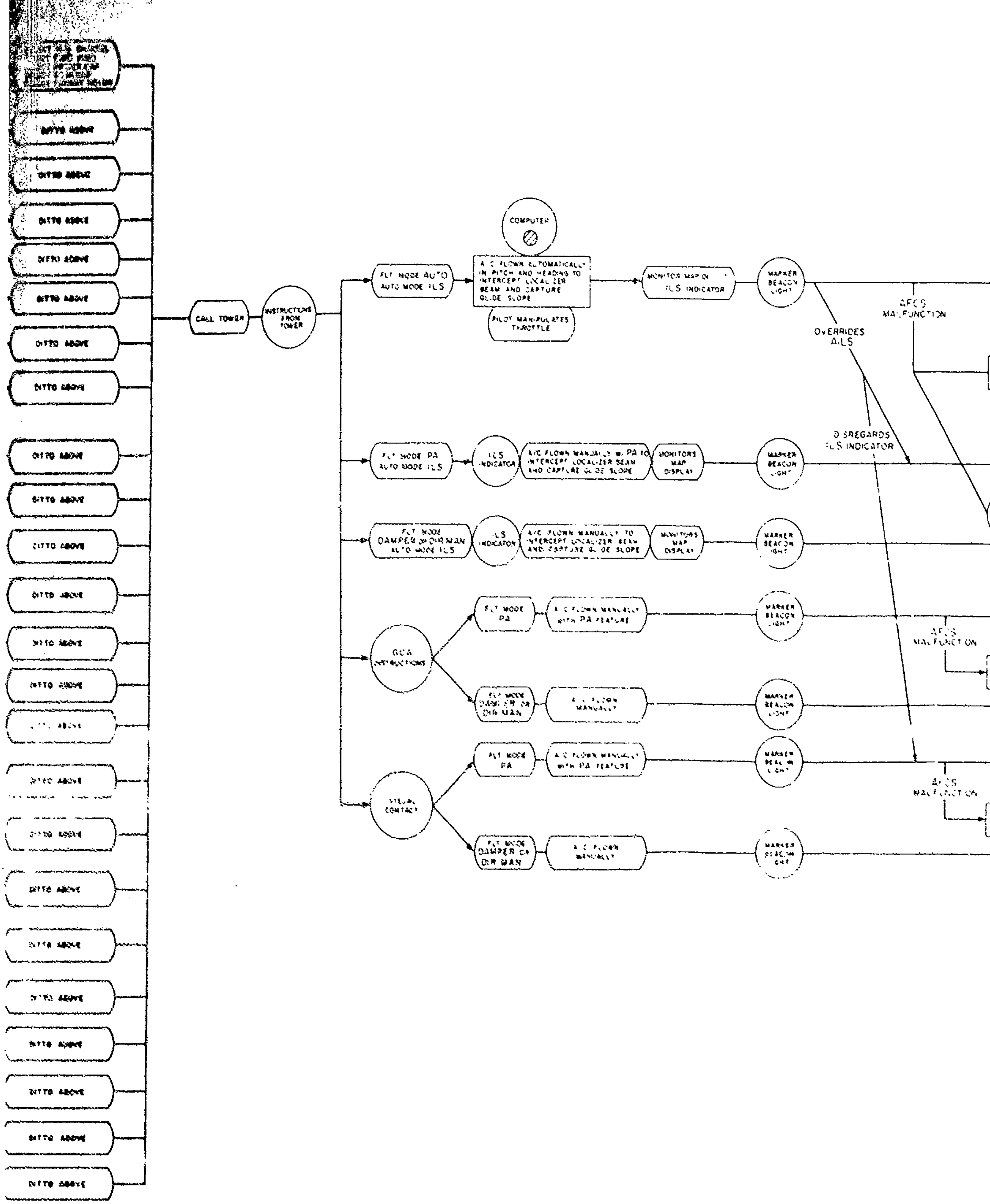



FIGURE 2 ALTERNATE EVENT SEQUENCES CULMINATING IN

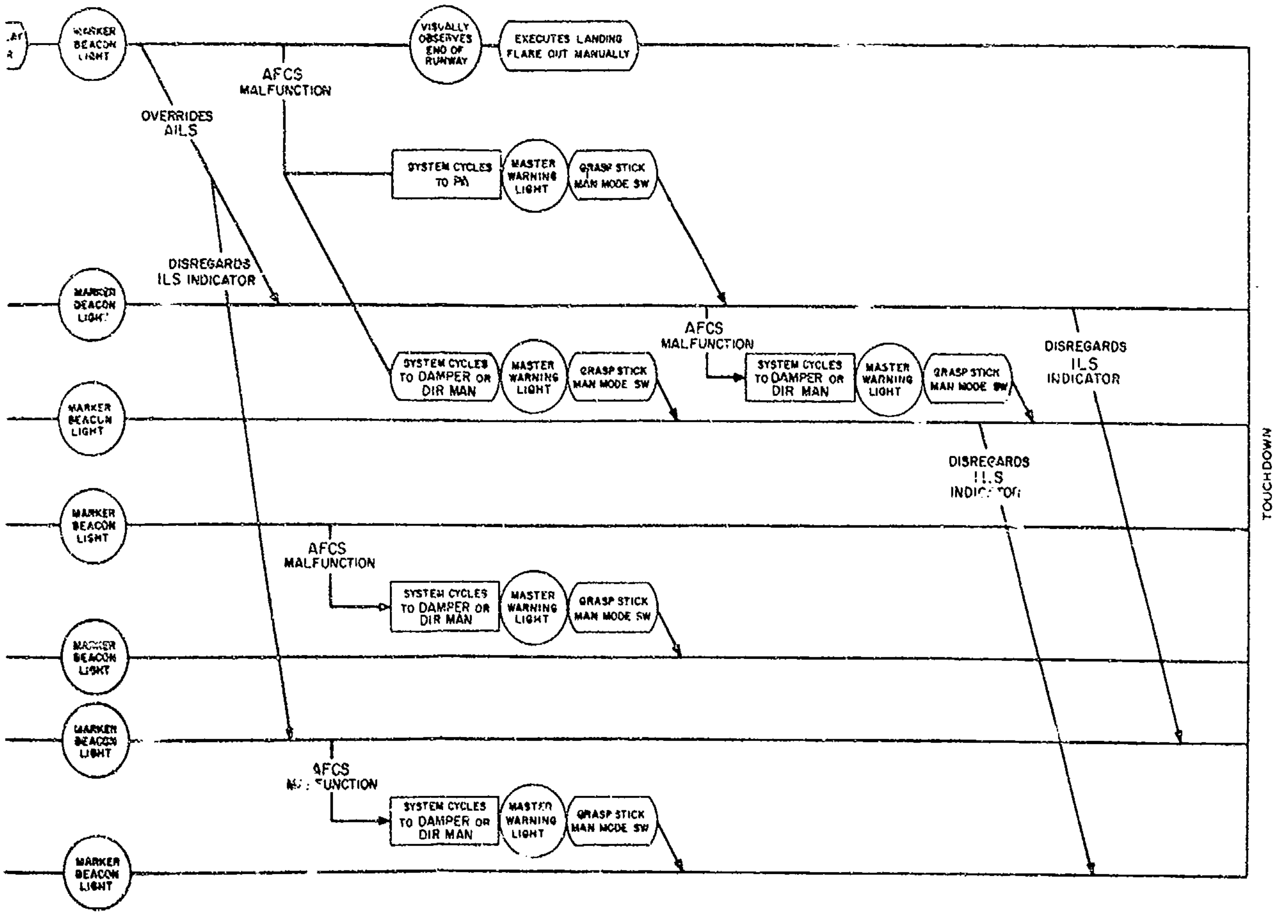



CESSFUL RETURN TO BASE AND LANDING

4


DITTO ABOVE
CALL TOWER
INSTRUCTIONS FROM TOWER
COMPUTER
FLT MODE AUTO AUTO MODE ILS
A/C FLOWN AUTOMATICALLY IN PITCH AND HEADING TO INTERCEPT LOCALIZER BEAM AND CAPTURE GLIDE SLOPE
PILOT MANIPULATES THROTTLE
MONITOR MAP OR ILS INDICATOR
MARKER BEACON LIGHT
AFCS MALFUNCTION
OVERRIDES AILS
DISREGARDS ILS INDICATOR
FLT MODE PA AUTO MODE ILS
ILS INDICATOR
A/C FLOWN MANUALLY W/ PA TO INTERCEPT LOCALIZER BEAM AND CAPTURE GLIDE SLOPE
MONITORS MAP DISPLAY
FLT MODE DAMPER or DIR MAN AUTO MODE ILS
A/C FLOWN MANUALLY TO INTERCEPT LOCALIZER BEAM AND CAPTURE GLIDE SLOPE
GCA INSTRUCTIONS
FLT MODE PA
A/C FLOWN MANUALLY WITH PA FEATURE
FLT MODE DAMPER OR DIR MAN
A/C FLOWN MANUALLY
VISUAL CONTACT

5


MARKER BEACON LIGHT
VISUALLY OBSERVES END OF RUNWAY
EXECUTES LANDING FLARE OUT MANUALLY
AFCS MALFUNCTION
OVERRIDES AILS
SYSTEM CYCLES TO PA
MASTER WARNING LIGHT
GRASP STICK MAN MODE SW
DISREGARDS ILS INDICATOR
SYSTEM CYCLES TO DAMPER OR DIR MAN
TOUCHDOWN

6

TABLE I

Combinations of Navigational Modes and Flight Control Modes

| Major Navigational Mode | DL MAX-RNG | | | AUTO NAV | | | MAP DISPLAY | | | | | VISUAL CONTACT | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Navigational Sub-Mode | | | | | | | TACAN | | ADF* | | | | |
| Navigational Sub-Sub Mode | | | | | | | | | DL | CMD | DL and CMD | | |
| Flight Control Mode | AUTO | PA | DAMPER or DIR MAN | AUTO | PA | DAMPER or DIR MAN | PA | DAMPER or DIR MAN | PA DAMPER or DIR MAN | PA DAMPER or DIR MAN | PA DAMPER or DIR MAN | PA | DAMPER or DIR MAN |

*Under the ADF navigational mode the flight control modes of PA, DAMPER (pitch and yaw) and DIR MAN are combined for further simplification of the diagram.

The antecedents to each of the states were traced back to a common origin just after the recovery from armament launch terminating the attack phase. Following the recovery from the attack the pilot contacts GCI for instructions concerning either reattack or return to base.

Although it is possible under certain circumstances to change directly from any one of the return-to-base courses of action to any other one of the 12 courses shown on the diagram, not all of the possible pathways for doing so are indicated. The rules used for determining which pathways were shown on the diagram are as follows:

1. Within each of the navigational modes, pathways are shown which indicate how to change from any flight control mode to any other flight control mode.

2. Among the different navigational modes, the pathways shown are those which indicate how to change from any navigational mode to an equally sophisticated mode or to a less sophisticated mode. For the purpose of constructing this diagram the DL and AUTO NAV modes were considered to be equally sophisticated. Both of these modes were considered to be more sophisticated than the Map Display mode, which is, in turn, more sophisticated than the Visual Contact mode. Within the Map Display mode the TACAN sub-mode was considered more sophisticated than the ADF sub-mode. The three ADF sub-sub-modes were considered to be equally sophisticated.

3. For changes from one navigational mode to another, the only pathways shown are those which indicate a change from the most sophisticated flight control mode within a navigational mode to the various flight control modes within another navigational mode. For the purpose of constructing this diagram the AUTO mode was considered to be the most sophisticated. The next most sophisticated was PA (pilot assist) which was followed by the DAMPER-DIR MAN combination.

Table II summarizes the pathways among the various courses of action that are shown in the return-to-base phase diagram. An X in a cell indicates reciprocal pathways between the courses of action indicated in the column and row headings. An arrow in a cell indicates that the diagram shows a unidirectional pathway leading from the course of action indicated in the column heading to the course of action indicated in the row heading.

It will be noted that for each of the 13 alternative return-to-base courses of action shown in Figure 2, two alternatives are indicated in the terminal area. These correspond to the availability or non-availability of TRACAL facilities.

It is assumed that regardless of the course of action followed in the return-to-base phase the pilot will call the tower for instructions prior to landing. Therefore, all courses of action are shown converging at this point. Following this, various sequences are shown which represent the alternative landing courses of action possible depending upon tower instructions, facilities available, weather and

TABLE II

Summary of Pathways for Changing from One Course of Action to Another

| | | Auto Mode DL MAX RNG | | | Auto Mode AUTO NAV | | | Map Display Tacan | | Map Display ADF | | | Visual Contact | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | flt mode AUTO | flt mode PA | flt mode DAMPER or DIR MAN | flt mode AUTO | flt mode PA | flt mode DAMPER or DIR MAN | flt mode PA | flt mode DAMPER or DIR MAN | ADF - DL | ADF - CMD | ADF DL and CMD | flt mode PA | flt mode DAMPER or DIR MAN |
| Auto Mode DL-MAX RNG | flt mode AUTO | | X | X | ↙ | | | | | | | | | |
| | flt mode PA | X | | X | ↙ | | | | | | | | | |
| | flt mode DAMPER or DIR MAN | X | X | | ↙ | | | | | | | | | |
| Auto Mode AUTO NAV | flt mode AUTO | ↙ | | | | X | X | | | | | | | |
| | flt mode PA | ↙ | | | X | | X | | | | | | | |
| | flt mode DAMPER or DIR MAN | ↙ | | | X | X | | | | | | | | |
| Map Display Tacan | flt mode PA | ↙ | | | ↙ | | | | X | | | | | |
| | flt mode DAMPER or DIR MAN | ↙ | | | ↙ | | | X | | | | | | |
| Map Display ADF | ADF - DL | ↙ | | | ↙ | | | ↙ | ↙ | | X | X | | |
| | ADF - CMD | ↙ | | | ↙ | | | ↙ | ↙ | X | | X | | |
| | ADF- DL and CMD | ↙ | | | ↙ | | | | | X | X | | | |
| Visual Contact | flt mode PA | ↙ | | | ↙ | | | ↙ | | ↙ | ↙ | ↙ | | X |
| | flt mode DAMPER or DIR MAN | ↙ | | | ↙ | | | ↙ | | ↙ | ↙ | ↙ | X | |

traffic conditions, possible system malfunctions, etc. The part of the diagram representing the landing phase was constructed using the same procedure as was used for the return-to-base phase. States of the system from which successful touchdown can be made were listed and then the antecedents to these were traced back to a common origin at the point where instructions are received from the tower. Any one of the courses of action that may be used during the landing phase may be terminated under certain conditions if it becomes necessary for the pilot to go around. This alternative is not diagrammed in the interest of simplicity.

The structure of the diagram presents what appears at first glance to be a rather complicated program for the pilot. This apparent complexity persists even though a number of simplifications were introduced to reduce the number of alternative courses of action shown on the diagram. Careful study, however, reveals that, once a particular course of action is initiated, it will usually be carried through to completion. A change in a course of action will be made only if some event occurs to render this ongoing course of action inappropriate. The occurrence of such an event is signalled to the pilot, and then either he makes the appropriate response, or the system makes the appropriate response automatically. In instances where it appears that insufficient information is presented to him concerning the appropriate response to make, his standard operating procedure is to make the response that will put the system in the next most sophisticated mode of operation.

## CLASSIFICATION OF POSSIBLE EVENT SEQUENCES

It should be emphasized that the diagrams shown in Figures 1 and 2 indicate only an extremely small fraction of sequences of events that might occur during the attack, return-to-base, and landing phases of the mission. This is a result of the procedure used in constructing the diagrams. It is probably worth repeating that the various sequences were constructed by starting with a relatively few states of the system that characterize the successful completion of a mission phase, and then specifying the antecedent events in such a way as to show how all of the sequences may originate from an arbitrary common point. Only in a few instances (those sequences in Figure 1 terminating in a cross-hatched rectangle indicating that the attack is broken off) is there an indication of a course of action that does not result in successful completion of a mission phase.

Consideration of some of the possible courses of action that do not result in the successful completion of a mission phase led to the development of a general classification scheme for showing the various possible kinds of event sequences that might occur. These sequences are defined by various combinations of and relationships between the following factors: (1) anticipation of an event and provision of an appropriate response for it, (2) the pilot's diagnosis of the event, and (3) the nature of the pilot's response.

An event whose occurrence renders an ongoing course of action inappropriate for the successful accomplishment of a mission objective may be put into one of three classes. One class is composed of all those events that are anticipated and for which appropriate responses are provided in the system design and in the pilot's training program (Type I events). A second class is composed of events that can be anticipated but for which no specific appropriate responses are provided (Type II events). The responses may not be provided either because their cost is prohibitive or because no specific appropriate responses are known. A third class is composed of those events that may occur during a mission but which are unknown to the system designers and the pilot prior to their occurrence (Type III events). Since these events cannot be anticipated no specific appropriate responses for them can be provided, either in the design of the system or in the pilot's training program.

An event sequence may start with the occurrence of any one of these three types of events. The outcome of a sequence depends upon the pilot's diagnosis of the event and the nature of his response. When an event from any one of these classes occurs the pilot may diagnose it correctly, or he may diagnose it incorrectly, or he may fail to diagnose it. For a well designed system and an adequately trained pilot it may be expected that most frequently the pilot will make a correct diagnosis of Type 1 events. For Type III events, on the other hand, the probability may be quite high that the pilot will either diagnose the event incorrectly or fail to diagnose it.

Following the diagnosis of an event, regardless of whether it is correct or incorrect, the pilot may make a response appropriate to the diagnosis, or he may make a response that is inappropriate to the diagnosis, or he may make no response. With a well designed system and an adequately trained pilot it may be expected that when a Type I event is correctly diagnosed, the pilot will most frequently make the appropriate response. The fact that no specific response is provided in the system design or in the pilot's training for Type II and Type III events does not necessarily mean that the pilot cannot make some response that would be appropriate for one of these events. Although the probability may be quite low, it is conceivable that a response or combination of responses that was provided for some anticipated event may prove effective for a Type II or Type III event.

A diagram illustrating the kinds of event sequences resulting from this method of classification is presented in Figure 3. The diagram shows only the sequence that may result when a Type I event occurs. The structure would be identical for both Type II and Type III. The letters S and U at the bottom of the diagram indicate successful and unsuccessful outcomes, respectively, of the individual sequences of events in terms of the mission objectives. The various sequences have also been labeled with lower case letters (a, b, c, ..., u.) in order that they may be more easily identified in the following discussion.

The sequences of events considered above in the analysis of the various phases of the F-106/MA-1 mission were a-type sequences. The various courses of action that were diagrammed represented appropriate responses made to correctly diagnosed events that were anticipated in the design of the system and in the pilot's training program.

Let us now consider some of the other possible kinds of event sequences originating with Type I events. It is possible for the pilot to diagnose the event correctly but to make an inappropriate response. This might come about as a result of poor coding of controls and control setting positions or through inadequate training in the operation of the system. In many cases making an inappropriate response would be disastrous (sequence d). On the other hand, it is possible that the pilot may be informed of the incorrectness of the response by means of feedback from the system or from the performance of the response itself. If such is the case, the response may be corrected either in time to result in a successful outcome (sequence b) or too late to result in a successful outcome (sequence c). It is also possible for an event to be diagnosed correctly but for no response to be made. The outcome here would of course be unsuccessful (sequence g). In the case where "no response made" refers only to a delay in making a response, there are two possible event sequences. One of these (sequence f) represents the case where the response is made too late to be effective. The other sequence (e) places the pilot back at either 1 or 2 on the diagram.

If the pilot diagnoses a Type I event incorrectly and makes a response appropriate to his diagnosis, the outcome may be unsuccessful (sequence h). There is another possibility here, however. Since the response is inappropriate for the actual event, if the pilot's displays provide good feedback information, he will make a new diagnosis

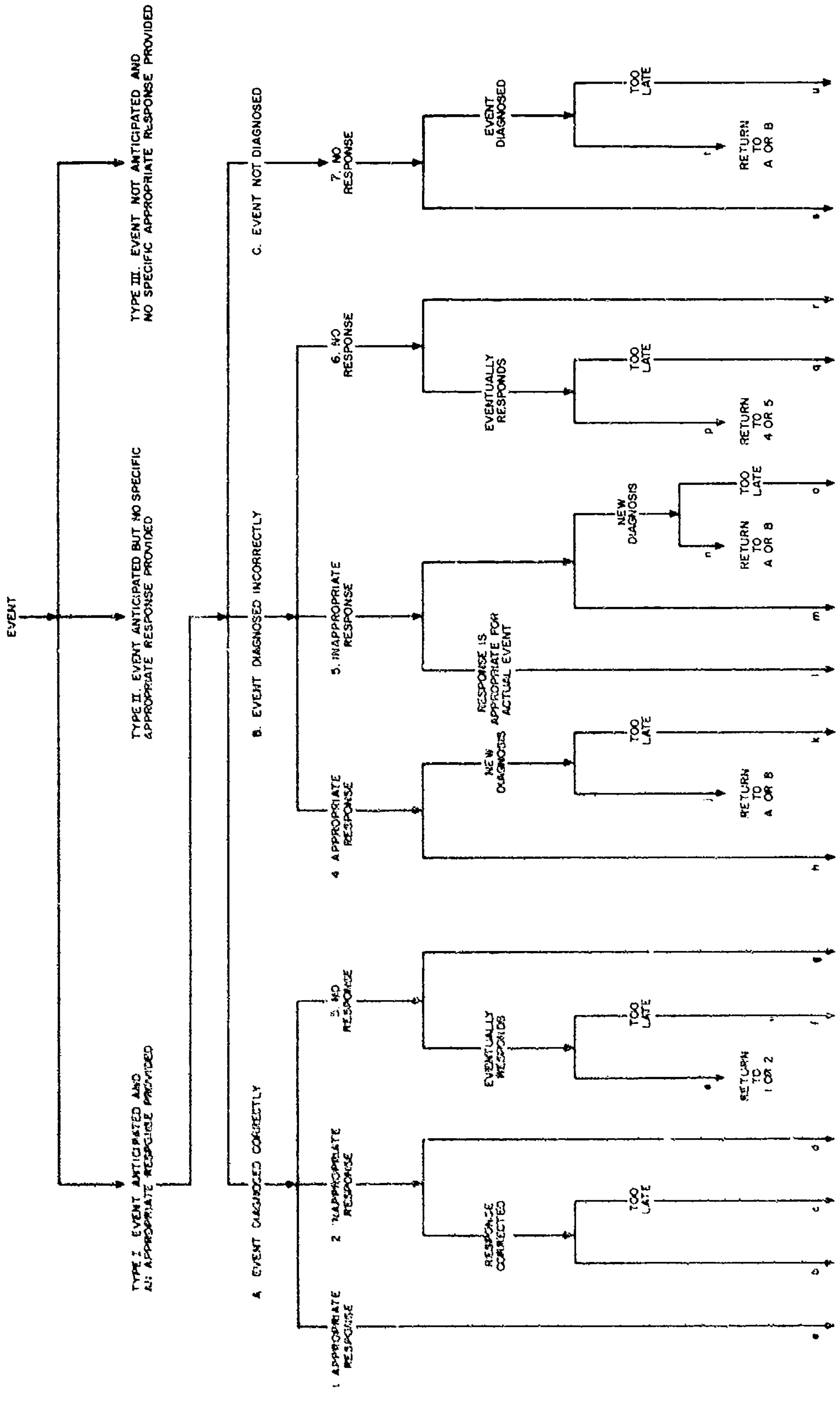



FIGURE 3. POSSIBLE KINDS OF EVENT SEQUENCES

of the state of the system. This may occur too late to be of any value (sequence k), or it may start a new sequence at either A or B on the diagram (sequence j). When an event is diagnosed incorrectly and a response inappropriate to the diagnosis is made there is some low probability that the response will be appropriate to the actual event (sequence l). The more likely outcome, however, of an inappropriate response made to an incorrectly diagnosed event is failure (sequence m). Once again there is the possibility of a new diagnosis which may occur too late (sequence o), or may start a new sequence at either A or B (sequence n). In the case where an event is diagnosed incorrectly and no response is made the outcome may be unsuccessful (sequence r). If some response is made eventually it may be too late to be effective (sequence q) or it may start a new sequence at either 4 or 5 on the diagram (sequence p).

If a Type I event is not diagnosed it is reasonable to expect that no response will be made. The outcome of this, of course, is unsuccessful (sequence s). Once again, however, there is the possibility that a diagnosis will eventually be made. If it is made, the sequence either starts over at A or B on the diagram (sequence t) or if the diagnosis is made too late the outcome is unsuccessful (sequence u).

The question may be asked, "If the kinds of possible event sequences are the same for Type II and Type III events as for Type I events, why make a distinction among these three types of events?" The answer to this question is that the probabilities of occurrence of the individual sequences are different for the three types of events. For example, consider sequence a. While it may be the most probable of all the sequences when a Type I event occurs, its probability of occurrence may be quite low for a Type II event, and perhaps it may be the least probable of all the sequences when a Type III event occurs.

In view of the fact that the manner of conceptualizing decision making was arrived at through the study of examples of only one of the several possible kinds of event sequences, the generality of this conceptualization was subjected to examination. The conclusion was reached that no modification of the concept was required in order for it to be generally applicable.

The decision problem for the pilot is the same regardless of which type of event occurs. While it is true that the pilot may have had no specific training in the diagnosis of Type III events, for example, the problem confronting him when one of these events occurs is the same as the problem facing him when a known event (Type I or Type II ) occurs. In all cases the decision required is a determination of the state of the system. Although the probability of a correct diagnosis may be lower for Type III events, the essential characteristics of the decision process are the same. No matter how novel the event, if it is sensed at all, it presumably has some features in common with known events. The response that has the highest probability of being made is a response appropriate to the known event most similar to the diagnosed event.

The analysis of the various possible kinds of event sequences also illustrates some of the advantages of a manned system over a completely automatic system. One of these advantages may be realized in the case of Type III events. Since these events are unknown prior to their occurrence, they cannot be anticipated and an automatic system cannot be specifically designed to cope with them. While the probability of a man correctly diagnosing and appropriately responding to one of these events may not be very high, it is, nevertheless, much higher than it would be for an automatic system.

An advantage may also be realized from having a man in the system in the case of Type II events. These events are those that can be anticipated but for which no specific appropriate responses are provided. Although no specific responses have been provided, the man has a large program of responses appropriate for other events. There is some probability, however low, that a response or responses provided for Type I events may prove effective against a Type II event. The required complexity of automatic airborne equipment designed to imitate the man in this respect is presently prohibitive in terms of size, weight, and dollar cost.

There is another point to be noted in reference to the advantages of a manned system over an automatic system when both Type II and Type III events are considered. The response made by the man to one of these events may not be effective in coping with the event. It may, however, alter the state of the system so that it is then characterized by the existence of a Type I event, which may have a high probability of being correctly diagnosed and for which an appropriate response has been provided.

## SYSTEMS DESCRIPTION

It is clear from the foregoing analysis that the operator of a weapon system is not so concerned with choosing among alternative courses of action as he is with deciding what the momentary state of the system is. Once a diagnosis is made, the proper course of action is specified by operating rules implicit in the design of the system. In other words, the system possesses a built-in operating logic of the form: if event E occurs then make response R. The set of all such events together with their responses constitutes what might be called the program of the system.

All weapon systems have programs of this kind. Provision is made for detecting the occurrence of some restricted set of events, or classes of events, $\Omega = [E_1, E_2, \text{---}\ E_i, \text{---}\ E_m]$, where each E may be either a single discrete event such as the occurrence or non-occurrence of some particular kind of countermeasure or else a class of events such as the set of all deviations from desired course greater than some minimum. The events provided for in a particular program are selected from a much larger set, all members of which have the property that their occurrence would prevent the successful accomplishment of the mission or at least would lower the probability of success if nothing were done in counteraction.

The response provided by the system is designed to counteract the effects of the event that occurs; i.e., it is designed to restore the probability of completing a successful mission. It is therefore called an adaptive response.

In an unmanned system the program is, of course, mechanized in the system. In a manned system the program is usually only partly mechanized with the man providing the remaining detection and logic functions. A program may be large or small depending upon the number of events the designer feels must be considered in order to have a successful system and upon the cost of providing for them in the program.

When choosing a program for a system the designer attempts to find a satisfactory tradeoff among a number of quantities. The first quantity is the a priori probability that each particular event will occur during a mission. Some events are much more likely than others. Secondly, there is associated with each event some measure of its threat to the successful accomplishment of the mission. These, too, cover a considerable range of values. Frequently occurring events that are effective in disrupting the mission must obviously be compensated for in any practical system. For example, most missiles have guidance systems of one kind or another in order to compensate for perturbations arising from initial aiming errors, rough air, instability, and so on. On the other hand, the program might contain no provision for even a completely disastrous event if it were felt that the probability of its occurrence were very low.

A third quantity to be considered when choosing a program is the cost of providing for each event in the program. The cost may be weight, space and/or dollars. The cost comes from at least two sources, (1) the cost of equipment for sensing or detecting the occurrence of the event, and (2) the cost of providing an appropriate response for the system to make should the event occur.

A fourth quantity that enters into the tradeoff is the probability that the response will be effective in counteracting the effects of the event. For example, most airplanes carry fire extinguishing systems to be used in the event of a fire. This equipment is not always successful in putting out a fire, and yet it must have a sufficiently high probability of success in order to be worth carrying.

When selecting a program for some weapon system the designer is, in a sense, actually making tactical decisions for the system and the process is theoretically susceptible, at least, to a description in terms of decision theory. It is possible in principle, for example, to compute the expected value of a system having a particular program. This could be done again for the same system with different programs, and that program yielding the highest expected value could then be chosen. In a sense this is what is done during the planning stage for a weapon system, even though it may not be practical to conduct the formal exercise.

In the planning phase the mission for the weapon is defined. This is a statement of what the weapon must do. For example, it must fly 1000 miles, drop a bomb weighing a certain amount with an accuracy of such an amount and return to base under all weather conditions. Next, the designer tries to decide what he must build in order to be able to do the missions at all. At this point he may consider alternative kinds of systems, i.e., a missile, a manned aircraft, and so on. These decisions involve program making, because, although each basic type of weapon might be capable of performing an uneventful mission, that type will be chosen that offers the highest expected value in the face of the major events that are expected to occur during a typical mission.

When the basic type of weapon is chosen, then detailed program making becomes one of the major concerns of the system designers. Since the interest of this project lies with manned systems it will be assumed that a manned system has been chosen. The fact that a manned system was chosen probably indicates that the program deemed necessary for the successful employment of the weapon is a large one and that the occurrence of some of the events in it cannot easily be detected automatically.

But because it is a manned system the program is obliged to assume some special characteristics, one of which tends to complicate the system while a second tends to simplify it.

The first characteristic is concerned with the redundancy that must be built into the system because there is a man in it. That is to say that a large subset of the events provided for in the program are events of equipment malfunction. Thus, if event $E_1$, a failure, occurs, then response $R_1$, an alternate mode of operation, is provided, in order, at least, to return the aircraft safely to base if not to continue its mission. These event-response pairs range in kind from direct counteractions to the event, as in the case of fire extinguishing, to the selection of alternate modes of performing the mission, as might be the case when an optical mode is used as backup for a radar. It should be noted in contrast that missiles are not normally built this way now, and therefore an equipment failure in a missile has a high probability of resulting in an unsuccessful mission.

The switching necessary to make the response, R, is most frequently an operator function in manned systems. This is true even though the switching could be performed automatically. This leads to the second characteristic of manned systems, namely, that the man may be required in the system only to accomplish a small part of the program but that, since he is there for this purpose, he is called on for other parts of the program as well.

Consider an extreme and fictional example. Suppose that the primary reasons for employing a manned interceptor are (1) to make a positive visual identification of a target before firing, (2) to achieve radar lockon to a target in the presence of ground clutter, and (3) to act against certain countermeasures that the enemy might employ. Now it would be possible to build an interceptor system that would carry the man as a passenger except for the performance of those three functions. However, no one at this time would consider it worth while to do so. Since the man is already there at great expense he might as well be used up to the efficient limit of his capability. Hence, he is given responsibility for much more of the program than the three events for which he is primarily responsible.

Manned systems possess some other attributes of interest that may or may not contribute towards the success of a mission. One of these is flexibility. Let some event, $E_k$, occur during a mission where $E_k$ was not originally provided for in the program of the system. A manned system compared with an unmanned system stands some chance of responding correctly to this event if it can be detected. Crudely stated, the man is able by inductive reasoning to classify the new event as being similar to some event already included in the program, and the response designated for the included event may be appropriate to the unexpected event.

A second way in which flexibility may be achieved is in the sensing of the occurrence of particular events. Normally a system, particularly an unmanned system, accomplishes the sensing or detection of the occurrence of each event in the program by means of a particular set of inputs provided for the purpose. For example, the position of an aircraft on final approach may be detected by means of a set of ILS localizer and glide path signals. Should these signals be denied to the system for whatever reason then the event goes undetected and the probability of mission success is decreased. Manned systems are characteristically flexible in this respect in that alternative methods of detection can often be improvised. This is particularly true of complex events. For example, suppose that some manned aircraft were intended to make instrument approaches on low frequency radio ranges. The aircraft attempts to make such an approach but finds that the low frequency receiver is out of commission. However, automatic direction finding equipment is available for detecting the bearing of the range station. It is now possible to fly exactly the same approach using visual ADF indications and compass headings as would have been flown with the low frequency range audio signals, even though this procedure was not intended to be used when the system was designed. Flexibility of this type is not commonly found in unmanned systems.

The above discussion is intended to show that as a consequence of the way in which systems are designed, it is possible to anticipate most of the decisions the operator of the system will be expected to make. These are of the diagnostic type; the operator is trying to decide what the state of his systen is or will be. Many of these decisions are "easy" to make, the information displays showing clearly what is happening. But many of the decisions are difficult. The information is noisy or indirect or it may (commonly) be displayed in bits and pieces through a number of instruments, requiring integration by the operator.

How the human makes decisions of this kind has recently become a subject of great interest. The interest has been sparked by the development of statistical decision theory and game theory in mathematics and economics. Psychologists have taken up the new models and are experimenting to determine how well they fit in the case of real human decision making under laboratory conditions.

Immediate application of the models to the case of pilot decision making with the expectation of useful quantitative results is premature at this time. Nevertheless, it can be assumed with some confidence that in the future the systematic thinking about human decision making in real life situations will derive from this work. Therefore, it is of interest to review briefly the current thought on the problem.

## APPLICABILITY OF VARIOUS DECISION THEORIES TO THE AIRBORNE DECISION-MAKING PROBLEM

This section very briefly outlines in general terms some of the major theories concerned with decision making and discusses the possible applicability of the theories to the airborne decision-making problem. A detailed treatment of the historical development of the theories, some of the special problems associated with each theory, and attempts to test various hypotheses may be found in a review article by Edwards (77). More comprehensive and rigorous statements of the various theories may be found in the following references: Girshick (78), McKinsey (86), Chernoff (30), Thrall, Coombs, and Davis (51), Wald (52) and VonNeumann and Morgenstern (88).

### THEORY OF RISKLESS CHOICES

The theory of riskless choices is applicable only to the choices made by what is termed an "economic man." It is assumed that economic man has complete information. He knows all of the alternative courses of action available, and he knows what the result or outcome of each of the courses of action will be. Economic man is assumed to be infinitely sensitive, and the alternatives available to him are assumed to be continuous, infinitely divisible functions. It is further assumed that economic man is rational. Rationality implies that he can weakly order the utilities of the outcomes of the alternative courses of action, and that he makes his choice so as to maximize utility. According to this theory, economic man maximizes utility by choosing the alternative course of action having the outcome with the highest utility.

This theory is not applicable to the practical airborne decision making problem. One may be willing tentatively to make the assumption that the pilot meets the requirements of rationality. The assumptions concerning infinite sensitivity may be abandoned (as they have in some versions of the theory). The assumption that the pilot has complete information, however, cannot be made. Even though he may know in most cases what the available alternative courses of action are, he never knows with complete certainty what the outcome of any given course of action will be.

### THEORY OF RISKY CHOICES

The theory of risky choices takes into account the fact that an individual who must make a choice never has complete information in advance about the outcome of his choice. The choice situation is characterized by the existence of two or more alternative courses of action, for each of which there are two or more possible outcomes. The theory requires that the individual making the choice must know the alternative courses of action. He must also know the possible outcomes for each of the courses of action although he does not know which outcome will actually occur.

It is assumed that the individual can assign a probability of occurrence and a utility to each possible outcome. According to the theory the individual chooses his course of action in such a way as to maximize the expected utility. The expected utility of a given course of action is calculated by multiplying the utility of each of the possible outcomes by its probability of occurrence and summing these products across all of the possible outcomes.

This theory is similar in some respects to the version of decision theory derived from detection theory that is discussed elsewhere in this paper. Both theories take into account the probabilistic nature of the individual's knowledge about events, and both consider the costs and values or utilities of possible outcomes. A major difference between the two theories is the aspect of the individual's behavior that is focused upon. The aspect of choosing emphasized by the theory of risky choices is the weighing of alternative courses of action to determine which should be taken. Detection theory, on the other hand, emphasizes the discrimination aspect of choosing and considers the course of action to be determined by the results of the discrimination. Thus, of the two theories, detection theory seems to be the more applicable to decision making as it is conceptualized in this report. Even when decision making is conceptualized in terms of selecting an alternative there are serious difficulties in applying the theory of risky choices to practical situations. These difficulties are concerned with the assignment of probabilities and utilities to the various possible outcomes. Until considerably more work is done on the problems of scaling utilities, relating subjective estimates of probabilities to objective probabilities, etc., there can be no adequate test of the applicability of this model to airborne decision making.

## GAME THEORY

Game theory provides, for certain well-defined situations, a set of rules for selecting a course of action from among the alternatives available. The theory is not concerned with the problem of how an individual actually selects a course of action in a situation to which the theory is applicable, but rather with the problem of determining what course of action should be selected. The rules for selecting a course of action are aimed at minimizing the maximum loss.

For a zero-sum, two-person, finite game, which incidentally, the pilot seldom, if ever, participates in, the requirements are as follow: (1) The pilot must know all the alternative courses of action available to him and all of the alternative courses of action available to his opponent. (2) He must be able to assign a payoff value to each combination of his own possible courses of action with each of his opponent's courses of action. (3) He must then know and use the rules for selecting the course of action that will minimize his maximum loss (or maximize his minimum gain).

Quite apart from the fact that the theory developed for zero-sum, two-person games is seldom applicable to the airborne decision-making situation there are other reasons for believing that an attempt to directly apply the theory would not be particularly profitable. While the pilot may know, in some cases, the alternative courses of action available to him, he does not necessarily know all of the alternative courses of action available to his opponent. Furthermore, the assignment of payoffs to the various combinations of each of his own courses of action with each of the opponent's courses of action represents a problem for which there does not seem to be an adequate solution at present.

It would seem that game theory may be most fruitfully applied in studies preliminary to the design of weapons system rather than to the decision-making problems faced by the pilot. That is to say, it appears useful in building a program for a system but not in the operation of the system as described here.

## A DECISION-MAKING THEORY OF DETECTION

The last theory to be considered here is the theory of visual detection developed by Tanner, Swets, et al., (14), from the earlier theory of signal detectability of Peterson and Birdsall (10). This theory has an intuitive appeal for application to the problem of pilot decision making even though it is true that no quantitative application is possible now. The justification for including it here is that it may be made to serve what Lazarsfeld (32) calls the organizing or linguistic as opposed to the predictive function of a model. That is to say that the concepts of the model may be useful in organizing a diverse set of observations at the linguistic level even though precise predictions of behavior cannot be made because quantitative data are not available.

Although the Tanner model began as a theory of visual detection, it has since been extended to include auditory detection and, more recently, a theory of recognition. A general theory of perception is the announced goal. The theory is mathematical. The experiments that Tanner has done to test the application of the theory depend upon quantitative prediction of behavior and therefore employ restricted and well-controlled experimental tasks and situations to an extent not feasible when studying pilot decision making.

At the risk of doing great violence to the theory and by deliberately ignoring its finer points, an attempt will be made to abstract from it what appears to be pertinent to the present study.

Originally the theory dealt with a situation in which the subject acts as an observer in a psychophysical experiment. The observer's task, for example, could be to look at a display which might be an evenly illuminated surface and, at a given time, to decide if a signal-a smaller test patch of near threshold illumination within the field— was or was not presented by the experimenter. The subject knew in advance what the signals look like and the time for making the observation was defined for him.

Unlike conventional psychophysical theory, Tanner postulates that the observer is really a noisy receiver of signals and that the decision about the presence or absence of the signal is based upon noisy information, the noise coming from random neural activity in the sensory system. Hence the decision-maker (to be thought of as a separate "compartment" of the observer) has the task of testing statistical hypotheses since an observation that appears to have come from a signal could actually have come from noise alone. Such an event, however, can occur only with some probability. Hence, two probability density functions can be defined. One, $f_N(x)$, describes the probability density of the observation, x, in a noise distribution. The other, $f_{SN}(x)$, describes the probability density of x in a signal-plus-noise distribution. Upon making a particular observation the subject must "decide" whether what he saw was signal or noise. Clearly if the probability were high that the observation, x, came from the signal-plus-noise distribution, compared with the probability that it came from the noise distribution alone, then the best bet would be to call the observation a signal. If the converse were true then the best bet would be to decide that a signal was not present and that noise alone was observed. The theory of signal detectability describes how an "ideal" receiver makes this decision in all cases. Tanner has essentially adopted this model and applied it to the human observer.

While it is intuitively clear that the observation should be called a signal if $f_{SN}(x)$ is very much greater than $f_N(x)$, in many cases of interest the probabilities are not so widely separated, yet a decision has to be made. The theory of signal detectability shows how this can be done according to a number of related criteria, each of which maximizes some characteristic of the outcome.

A useful relationship between $f_{SN}(x)$ and $f_N(x)$ is defined as the likelihood ratio $\ell(x) = f_{SN}(x)/f_N(x)$. The problem is to find the smallest likelihood ratio that one will accept and still call the observation a signal. Then all observations with likelihood greater than this will be called signals, and all observations with likelihood less than this will be called noise, or signal not present. This is the cutoff point. The theory shows a number of different ways of setting the cutoff, all of which meet the mathematical requirements of being an optimum criterion.

The criterion of interest here is called the expected value criterion in which

$$\text{the cutoff} = \beta = \frac{P(N)}{P(SN)} \cdot \frac{(V_R + K_F)}{(V_D + K_M)} .$$

P(N) and P(SN) are the <u>a priori</u> probabilities of no signal and signal respectively. It is intuitively reasonable that $\beta$ should be determined in part by the ratio of these probabilities. Suppose that each of these probabilities were 0.5, i.e., 50% of the time signals are presented and 50% of the time they are not, then $\beta = 1$. In turn this implies that other things being equal for an observation to be called a signal it should have at least a 50% chance of coming from the signal-plus-noise distribution and that all those with greater than 50% chance <u>should</u> be called signals i.e. $\ell(x) = f_{SN}(x)/f_N(x) \geq 1$. Suppose, in another case, that $P(SN) = 0.01$ and $P(N) = 0.99$. Now the minimum likelihood ratio should be set much higher in order to avoid a very large number of false alarms. It can be shown that if $\beta$ were defined only as $\beta = P(N)/P(SN)$ then the observer using this criterion would act to minimize his total error.

Now consider the second term in the expected value criterion. Here

$V_D$ = value of a detection (correct call "signal present")

$V_R$ = value of a rejection (correct call "no signal present")

$K_M$ = cost of a miss (signal present but not called)

$K_F$ = cost of a false alarm (signal absent but called as present).

Again consider the case where the a priori probabilities of signal and noise are equal, but in this instance let the value of a correct detection far outweigh the cost of a false alarm. Now it might be better to lower $\beta$ somewhat in order to catch a higher percentage of the true signals even at the cost of many false alarms. On the other hand if false alarms were very expensive compared to the value of correct detections then $\beta$ should reasonably be raised. Thus this criterion can be said to maximize the total expected value of the results of the decision process.

Actually, that $\beta$ is an expected value solution can be seen from the following: Let A represent the set of outcomes in which the observer says "a signal is present" and CA the set of outcomes in which he says "a signal is not present," then four outcomes are possible:

$SN \cdot A$ = a signal is present and is called present.

$N \cdot CA$ = a signal is absent and is called absent.

$SN \cdot CA$ = a signal is present and is called absent.

$N \cdot A$ = a signal is absent and is called present.

If

$V_{SN \cdot A}$ = value of the correct response $SN \cdot A$

$V_{N \cdot CA}$ = value of the correct response $N \cdot CA$

$K_{SN \cdot CA}$ = cost of the error $SN \cdot CA$

$K_{N \cdot A}$ = cost of the error $N \cdot A$

and if $P(SN \cdot A)$, $P(N \cdot CA)$, etc., are the probabilities of the joint events in question, then the expected value of the decision will be by definition,

$$EV = V_{SN \cdot A}\, P(SN \cdot A) + V_{N \cdot CA}\, P(N \cdot CA) - K_{SN \cdot CA}\, P(SN \cdot CA) - K_{N \cdot A}\, P(N \cdot A)$$

An optimum criterion would therefore be one that would maximize this expression. It can be shown with suitable manipulation, involving the substitution of a priori and conditional probabilities for the joint probabilities in the above expression, that maximizing of the expected value is equivalent to requiring that

$$P_{SN}(A) - \beta P_N(A) \text{ is a maximum, where}$$

$$\beta = \frac{1 - P(SN)}{P(SN)} \cdot \frac{(V_{N \cdot CA} + K_{N \cdot A})}{(V_{SN \cdot A} + K_{SN \cdot CA})} .$$

In a set of eight theorems, Peterson and Birdsall (10) show the relationship between an optimum criterion and the likelihood ratio. Of interest here are theorems 1 and 2.

Theorem 1: Denote by A the set of points for which the likelihood ratio $\ell(x) \geq \beta$. Then A is an optimum criterion $A_1$ ($\beta$).

Theorem 2: If A is an optimum criterion $A_1$ ($\beta$), then the set of points in A for which $\ell(x) < \beta$ has probability zero, and the set of points not in A for which $\ell(x) > \beta$ has probability zero.

The proofs may be seen in the reference article. Taken together, these things show that if the expected value of the decision is to be maximized then those observations with likelihood ratio equal to or greater than $\beta$ should be called signal present and those with likelihood ratio less than $\beta$ should be called signal absent, hence $\beta$ is shown to be the appropriate minimum or cutoff likelihood ratio.

In summary that part of the theory with which we are concerned deals with an observation, two probability density functions, a set of a priori probabilities, a set of costs and values and a rule for relating these quantities in such a way as to make an optimum decision about the observation.

What Tanner has done in his experiments is to show that this model and ramifications of it can be used to predict quantitatively the behavior of human observers in situations admitting of a test of the model. He has shown that observers can act according to the various decision criteria described in the theory. He has shown that these predictions are independent of particular experimental designs used. The model has been successfully used in audition as well as vision and has been able to achieve quantitative prediction in the case where the observer must recognize one of two signals in noise instead of the presence or absence of a single signal.

It is important to note that Tanner assumes that the noise is generated within the observer. This opens the door, as it were, to a liberal application of the theory beyond simple situations where it is possible to measure the quantities involved. Whether such applications are useful remains to be seen.

A decision is really the choice of one from a set of alternatives.

While the experimental work with the theory has dealt with simple yes-no alternatives or with the recognition of one of two possible signals, it is possible to consider large sets of alternatives. The theory requires that each of these occur with some a priori probability greater than zero and that the sum of the a priori probabilities over all alternatives equals one. It can be argued that by merely considering the $i^{th}$ alternative as a possible outcome the observer has assigned to it some a priori probability greater than zero. Otherwise he would not have considered it as a possible outcome in the first place.

The a priori probabilities assigned by the man are not necessarily the true a priori probabilities. Instead, they represent the observer's beliefs concerning the true probabilities. They are based upon his past experience, training and understanding. Obviously the observer can only act (decide) on the basis of subjective probabilities unless he is provided with information about the true probabilities. The theory does not demand that he have information about the true probabilities but only that a probability for each alternative exist. When the observer makes a decision he then is exposed, for the first time, to the consequences of a discrepancy between his assumed probabilities and the true probabilities, since it is then that he becomes aware of errors. The values and costs are at this point realized, and he finds that he does not realize his expected values. As a result of this finding he may modify his subjective ensemble of probabilities so as to correspond more closely to the true probabilities.

The ability to form likelihood ratios is assured by the noise assumption of the theory. Thus, for each alternative there exists an hypothesis, $f_i(x)$, the probability density that if the $i^{th}$ alternative exists the observation, x, results. Also, by the noise assumption for every i, $f_i(x) \neq 0$. Although, of course, for many alternatives it may be close to zero.

Finally Tanner shows that the theory may be extended to consider complex alternatives where multiple observations must be made to identify an alternative. Each complex alternative, $A_j$, consists of a sequence of simple alternatives $a_{j1}, \ldots a_{j2}, \ldots a_{ji}, \ldots a_{jn}$. Each simple alternative is associated with an observation, $x_i$. The set of observations, $x_i$, is combined into a single observation x, such that for the complex alternative $A_j$ there is the probability density function $f_{A_j}(x)$. This specifies the probability that if the $j^{th}$ complex alternative exists the particular sequence $x_i$ of observations results. Hence for each complex alternative a likelihood ratio can be determined based on the sequence of observations $x_i$ and the end result is again a single quantity as in the case of a simple alternative.

Some interesting results are obtained by regarding ordinary pilot decision functions in the light of this model. Consider, for example, the target marker on the search radar scope. The target marker is a small circle that is positioned on the search display by information sent up from the ground. It is supposed to indicate where the pilot should detect the target on the scope. From the point of view of the Tanner model, what the target marker does is to redistribute the a priori probabilities of seeing a target. Inside the marker the a priori probability is very high; outside the marker the a priori probability is very low — lower, in fact, than if there were no marker. Inside the marker, therefore, the pilot's cutoff, $\beta$, should be very low, permitting him to accept as target an observation with a low likelihood ratio. This, of course, is what happens. An observation does not have to be very greatly different from noise to be accepted as a target. If the target marker were not there, the same observation would be rejected and called "no target." Outside the target marker the pilot's $\beta$ should be unusually high and only observations with large likelihood ratio would be accepted as target. This is indeed the case and it has been shown that adding a marker to the scope decreases the probability of detecting a target outside the marker.

Consider a second example. A study of the detection and tracking of very weak targets was conducted with a radar simulator. Actually the experimenter presented no targets at all most of the time, since he wished to see if the observers would accept noise or clutter as targets under the conditions of the experiment. The observers refused to do this until the experimenter created what might best be called a competitive social situation surrounding the experiment. By this device the observers were induced to make numerous pseudo detections believing that they were genuine. What the experimenter did, of course, was greatly to inflate the value of a detection while practically eliminating the cost of a false alarm, thus permitting observations with very small likelihood ratios to be accepted as a signal.

Finally, consider a more tenuous example. A pilot is trying to decide whether or not to make some particular flight. He is deterred from doing so by unfavorable weather. The alternatives between which he must decide are (1) the weather will be good enough so that a safe flight can be made, (2) the weather will be sufficiently poor that the flight will be hazardous. He makes an observation, actually a complex observation, of the weather from the latest weather sequence, direct observation, etc., and (subconsciously) computes what amounts to a likelihood ratio between the probability density functions that (1) given the first alternative this particular weather observation would have occurred, and (2) given the second alternative the same observation would have occurred. His $\beta$ is set by the a priori probabilities, which, in this case, are given by the weather forecast, and by costs and values which here are derived from the importance of the trip and the cost of a mistake.

# PROBLEM AREAS REQUIRING EXPERIMENTAL STUDY AND SOME SUGGESTED APPROACHES

The purpose of this section is to consider some of the areas in decision making that require experimental and theoretical studies, and to suggest some ways of approaching these problems. The theoretical development of the area of decision making, extending from the early work on the theory of riskless choices to the recent work on statistical decision theory and game theory has a long history. However, it is only comparatively recently that any large amount of significant work has been accomplished in the way of testing various hypotheses experimentally under well controlled conditions.

At present experimental work is being carried out in the area of decision theory proper, and also in closely related areas such as problem solving and learning. It is unnecessary to review this work here, as reports of the results are readily available (28, 31, 32, 47, 48, 51, 79, 82). It is also beyond the scope of this section of the report to present detailed plans for a comprehensive program of research on decision making. Several such programs are in progress at the present time.

The need for both theoretical and experimental studies in certain specific areas became apparent during the course of the work on this study program. It is with these areas that this section is concerned. The mention of particular areas in need of research should not be interpreted as implying that good work is not being done or has not been done in these areas. In some instances the areas are mentioned because it is considered that additional experimental tests under a wide variety of conditions are needed. In other instances specific areas are mentioned in order to suggest approaches that are different from ones heretofore utilized.

## SUBJECTIVE PROBABILITIES

One of the areas most in need of additional experimental work is that concerned with subjective probability. Following the distinction drawn by Edwards (77) the phrase subjective probability is used here as "a name for a transformation on the scale of mathematical probabilities which is somehow related to behavior" rather than as "a name for a school of thought about the logical basis of mathematical probability." In the discussion of detection theory it was pointed out that the a priori probabilities utilized in decision making are not necessarily the true probabilities. The theory of risky choices also required that the individual make estimates of the probability of various outcomes, and the success of utility maximization is largely dependent upon the validity of these estimates. Although some research has been done on the problem of the relationship of subjective probability to objective probability, the area is still largely unexplored.

Information is needed about how the individual develops the concept of probability, how subjective probability is related to objective probability under a wide variety of environmental conditions, how probability estimates are utilized in everyday behavior, and the conditions under which probability estimates are changed due to experience with events. An analysis leading to a theoretical formulation of the individual's development and utilization of probability estimates would be particularly valuable. A possible approach is suggested in the following paragraphs.

It is a commonplace observation that people generally do not assign numerical probabilities to risky and uncertain events in everyday life. Except for the phrase "a 50-50 chance" most statements about risky events are non-numerical. It is probably safe to say that most people who use the phrase "a 50-50 chance" would define this in terms of "an even chance," or in some similar terminology rather than as a probability of 0.5 on the scale of mathematical probabilities. It may even be the case that persons who have had formal training in the mathematical conceptualization of probability, and who work with the scale of mathematical probabilities formally do not make use of the fineness of discrimination possible with this scale to any great extent in their everyday behavior.

Nevertheless, it may be observed that people generally do recognize that events differ in their probability of occurrence. The most obvious examples are to be found in activities that are generally classified as "games of chance." Almost anyone who has played craps knows some conventional bets, for example, "even money," "three to two," etc., for certain points. However, except for professional gamblers, very few people know the actual mathematical probability of any given point being made. The same thing is generally true of the non-professional poker player. He may know that the rule says "you don't draw to an inside straight." He doesn't know what numerical probability should be assigned to the occurrence of this event, but if he has played much poker he does have a subjective notion, based upon experience, that this event is not very likely to occur.

There is also some observational evidence that people use some kind of scale of subjective probability for referring to the likelihood of occurrence of events. The English language is replete with phrases such as "almost a sure thing," "a better than even chance," "highly doubtful," "practically impossible," etc. Presumably these and other phrases are estimates of probability spanning the scale of mathematical probabilities from 0 to 1. Unfortunately, because of the plethora of phrases available, and the wide variety of individual experiences, a determination of the relation of specific phrases to points or intervals on the scale of mathematical probabilities would have very little general value.

On the other hand, it would seem worth while to investigate the number of categories of subjective probability utilized in dealing with risky events. It is interesting to speculate that all individuals use about the same number of subjective categories even though the names used for the categories differ. The results of recent experimental determinations of the channel capacity for stimuli along simple dimensions by the method of absolute judgements are suggestive even though it is recognized that the estimation of probability is not equivalent to the absolute judgement of unidimensional stimuli. It is tempting to expect that an individual may use about seven categories, corresponding to estimates described in phrases such as (1) event will not occur, (2) almost impossible, (3) less than an even chance, (4) an even chance, (5) better than an even chance, (6) almost certain to occur, and (7) absolutely certain. Actually, it seems likely on the basis of casual observation that more than seven categories are used. However, it may be that even if a relatively large number of categories are used, the amount of information about objective probabilities transmitted by subjective estimates is no larger than if a smaller number of categories were to be used. This might result from the fact that the same subjective estimate is not always made for an objective probability.

Whether seven or some larger or smaller number of categories are actually used, or whether there is no uniformity among individuals or within the same individual under different conditions are, of course, questions that must be answered, not from casual observation and armchair speculation such as led to this discussion, but rather by the results of carefully designed and executed experimentation. Such experiments should be designed to determine not only whether the individual categorizes probability estimates at the level of verbal behavior, but also whether his non-verbal behavior in situations involving probabilistic events shows evidence of categorization of probability estimates.

## COSTS AND VALUES

Another area in which little is known about how the human behaves is that one concerned with the assignment of utilities or costs and values to outcomes. The experimental work in this area has been concerned for the most part with the measurement of utility for money. A few studies that have not utilized money payoffs have used commodities for which a monetary equivalent is generally known. In the experimental work on the decision making theory of detection Tanner and his associates have used money costs and values for false alarms, misses, hits, and rejections. Although this was expedient for the preliminary experimental work, more needs to be known about the scales of costs and values in a practical detection situation. It seems highly doubtful that a radar observer, for example, conceptualizes the value of a detection and the cost of a false alarm or a miss in terms of dollars. Nevertheless, there presumably is some ordering of the utility of outcomes. As was the case with subjective probability estimates, it is tempting to speculate that an individual works with a relatively small number of categories of costs and values rather than with a finely divided scale involving many discriminable intervals.

## EFFICIENCY OF DECISION MAKING

A number of studies within the framework of detection theory have been concerned with estimating the efficiency of the human observer as a decision maker. This is done by comparing the performance of the human observer with that of an "ideal" observer as a standard. The performance of the ideal observer is expressed as a ratio of probability of detection to probability of false alarm for different values of $\beta$ , the cutoff criterion, and for a given signal-to-noise ratio. This is a mathematical computation that has been worked out in a number of special cases, for example in the cases of a signal known exactly or a signal known except for phase, in the presence of Fourier series band-limited white Gaussian noise. The performance of such an observer is optimum in the sense that all of the information in the input is used in making the decision. The human observer is presented with the same signal and noise and his detection and false alarm rates are measured in an experiment. Since the human's performance must be less than or equal to that of the ideal observer the decrement, if any, is measured by computing the amount that the signal energy would have to be attenuated in order for the ideal observer to yield the same performance as the man. The ratio of this energy to the actual energy in the signal is a measure of the human observer's efficiency. The noise power, of course, is kept the same throughout.

This is one example of the kind of research that is being done in decision theory. Along with others of its kind it depends upon measurement of and control over signal energy and noise power. Some of the signals with which pilots deal are of this kind. It is possible to measure signal energy and noise power and to conduct experiments in reasonably strict interpretation of the model. With most signals of interest, however, this is not possible. It is meaningless, for example, to talk of the signal energy in an aircraft instrument reading. The model is able to handle such variables but the design of experiments under these circumstances becomes difficult.

## APPLICATION TO PILOT DECISION MAKING

According to Marill (7) a detection situation exists whenever the following five conditions are true:

1. On each "trial" one or the other of two mutually exclusive states S or $\bar{S}$ obtains. The a priori probability P(S) of the occurrence of S is assumed to be a fixed given number.

2. On each trial the subject (the "detector") brings about the occurrence of one or the other of two mutually exclusive events ("responses") R or $\bar{R}$.

3. Event $Q_1$, $Q_2$, $Q_3$, or $Q_4$ occurs on a given trial according as the joint event $S \cdot R$, $\bar{S} \cdot R$, $S \cdot \bar{R}$, or $\bar{S} \cdot \bar{R}$ also occurs on that trial.

4. The occurrence of the event $Q_i$ ($i = 1, \ldots, 4$) has a specifiable value, $v_i$ (the "payoff value" or "payoff") for the subject.

5. The following inequalities hold: $V_1 > V_3$; $V_4 > V_2$.

In the case of pilot decision making, introspection and analysis suggest that a process somewhat like the following may take place. The pilot is attempting to diagnose the state of his aircraft with respect to some variable, say geographic position. The pilot comes to the decision situation, and this is important, with an hypothesis concerning what the state is. He makes an observation such as the reading of a set of instruments. He then concludes, or decides, that the hypothesis is correct or incorrect.

The state S is the state that the instrument readings do in fact confirm the pilot's hypothesis and the state $\bar{S}$ is that they do not. $P(S)$ is therefore the a priori probability that the pilot's hypothesis is correct.

The response R is the conclusion by the pilot that his hypothesis has been confirmed; $\bar{R}$ that it has not been confirmed.

The events $Q_i$ are therefore:

$Q_1$ = The hypothesis is confirmed and the pilot concludes it has been confirmed.

$Q_2$ = The hypothesis is not confirmed and the pilot concludes it is confirmed.

$Q_3$ = The hypothesis is confirmed and the pilot concludes it is not confirmed.

$Q_4$ = The hypothesis is not confirmed and the pilot concludes it is not confirmed.

It is reasonable to suppose that each $Q_i$ has some value to the pilot, although it is obviously difficult to assign numbers to these. Nevertheless clause No. 5 appears to hold; that is, it is reasonable that

$$V_1 > V_3 \quad \text{and} \quad V_4 > V_2 \ .$$

Ignoring the $V_i$ for the moment it will be recalled that the general form for deciding in favor of alternative S, i.e., making the response R, is when $P(S)P_S(x) > P(\bar{S})\,P_{\bar{S}}(x)$, or whenever the likelihood ratio

$$\ell(x) = \frac{P_S(x)}{P_{\bar{S}}(x)} > \frac{P(\bar{S})}{P(S)}$$

where x stands for the observation, in this case the instrument readings. The term $P_S(x)$ may be interpreted as follows: $P_S(x)$ is the likelihood in the pilot's own mind that the observation he has made could belong to the set of those observations that confirm his hypothesis. Obviously, in order to give substance to this interpretation it is necessary to assume that the pilot introduces uncertainty somewhere in the observation process. Those who are pilots or have studied pilot behavior have no difficulty in making this assumption. It would appear, therefore, that ordinary pilot decision making can be reasonably interpreted in terms of detection theory. It remains to be determined how useful the interpretation can be.

The reader can try the exercise of formulating various common pilot decision problems in terms of the theory to see if any insight is gained. For example there is the problem of the false alarm, i.e., the "fat, dumb and happy" pilot who unaccountably acts in a way that is completely incompatible with the inputs he is getting. The event of a miss is equally serious. Here the pilot's hypothesis is correct but he interprets the observation as indicating a rejection of it, necessitating the formulation of a new hypothesis which must necessarily be wrong. This in turn may lower the threshold for a subsequent false alarm. Such behavior is the cause of many accidents. There is the difference in decision behavior that is observed when the pilot's inputs are coded in different ways, for example, contact versus instrument flight or pictorial versus symbolic instrument displays. This leads to interesting speculation concerning how the pilot generates uncertainty in the observation process and whether this may depend upon the relationship between the form of the input and the form in which the pilot's hypothesis is stored in his memory. The assumption that the pilot comes to the decision process with an hypothesis to be tested is basic to the present interpretation of the model and should itself be subjected to experimental verification. Many other implications of the model can be imagined and the difficulties of subjecting them to experimental test must be overcome in subsequent work.

## FINAL REMARKS

The bulk of this study has been concerned with a detailed analysis of the pilot's task in a modern and quite sophisticated weapon system. The details of this work have not been reported here, partly because of security considerations but also because no useful purpose would be served by doing so. This analysis showed clearly, in the opinion of the investigators, that the pilot's decision functions, in this system at least, are concerned with the diagnosis of the state of the system and only rarely with the choice of a course of action to pursue. In no sense does the pilot simply jump in his airplane, take off, and then decide what to do as he goes along. The mission, of course, is carefully planned in advance but the courses of action open to the pilot are largely built into the system. These are the modes of operation of which the system is capable. A mode is provided for each major state in which it is expected the system will find itself. The pilot is then to determine what the state is. Having done this he then adjusts the equipment to operate in the mode specified in advance for that state. His decision, then, is a diagnosis — a detection and recognition of the state of the system.

These conclusions led to some speculation concerning the nature of weapon systems in general. It was postulated that all weapon systems, both manned and unmanned, have what might be termed a program. The program is essentially a list of events that may happen to a system during a mission, together with a set of adaptive responses, each designed to compensate for the effects of an event so that the mission will be successful despite the event. Some comparisons between manned and unmanned systems were made in terms of their programs. It was shown that the man is in the system primarily to detect and recognize the occurrence of events that it is difficult to detect automatically. But once in the system he is given many other duties as a matter of economy.

Next, a brief review of the more prominent decision theories was made. Most time was spent on the model of Tanner's, because this seemed to correspond most closely with what the pilot does in operating a weapon system. The difficulties involved in obtaining the required quantitative information for use of the model were indicated. Some suggested approaches towards solving this problem were made. Finally a general form for application of the model to pilot decision problems was given.

What was not done, although it would have been desirable, was to provide a careful look at the implications of using the model in future studies of pilot decision functions. In those cases of interest it would appear that all important variables are subjective and use of the model may simply end in tautology. On the other hand it is not impossible that a way around this may be found. It would appear that this should be a subject for a separate study.

Practically nothing has been said about displays and controls for future systems, although it would be possible to speculate at some length using concepts stemming from decision theory. For example, there may be considerable merit to the idea of displaying probability estimates to the operator where such information is available. Indeed, such a display was proposed at one time by Hughes Aircraft Company but was ultimately abandoned because of construction difficulties. On the other hand it is possible to err in the opposite direction and present probabilistic information as if it were certain. This can lead to unfortunate decisions by the pilot.

It is regarded as premature at this time to attempt a discussion of displays and controls for future systems. So much depends upon the system itself that the display and control rules that are now available appear to be as far as one should go in this direction until a considerable body of experimental evidence can be assembled to support any new rules based upon decision theory.

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